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AGARD CONFERENCE PROCEEDINGS No. 268

Modeling and Simulation of Avionics Systems and Command, Control and Communications Systems

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

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AGARD Conference Proceedings No.268

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MODELING AND SIMULATION OF AVIONICS SYSTEMS AND COMMAND, CONTROL AND COMMUNICATIONS SYSTEMS.

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Copies of papers presented at a Meeting of the Avionics Panel held in Paris, France, 15–19 October 1979.

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- Improving the co-operation among member nations in aerospace research and development;
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- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
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- Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

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Published January 1980

ISBN 92-835-0255-8

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London, W1P 1HD

THEME

With continuing growth in system cost and complexity, simulation is becoming increasingly important to the military and civilian communities as a tool for design and evaluation of complex processes and systems. Among its uses are comparison of competing system concepts and architectures, prediction of system performance, optimization of system responses, analysis and verification of system designs, training of individuals and teams, and assessment of man-machine system performance. Because of its growing use and application to avionics systems and C^3 systems associated with airborne operations, the Avionics Panel of AGARD decided to devote its 38th Technical Meeting to a Symposium on this important subject.

Modeling and simulation of avionics and C^3 systems are heavily based on physical sciences, computer science, mathematics, and probability theory; yet the process of model development and experimentation is still very much an intuitive art. In contrast to manned simulators, the more complex system models tend to be "grown" rather than specified beforehand. In order to obtain favorable cost-benefits and effective utilization of any simulation, appropriate methodologies for development and implementation need to be established, application histories analyzed and lessons derived, and the economics of the simulation better understood. In recognition of these needs, this Symposium addressed simulation techniques and their applications to avionics and C^3 systems associated with airborne operations.

The program opened with a one-day tutorial session on simulation. The remainder of the symposium covered: modeling methodology, experimentation, validation, and applications. Emphasis was on Avionics and Airborne Command and Control, with papers covering the range from large-scale force-effectiveness and air defense simulations through flight simulators and real-time avionics simulations.

PROGRAM COMMITTEE

PROGRAM CHAIRMAN: Mr Joseph G.Wohl
Department Head
Command and Control Systems Architecture
The MITRE Corporation
P.O. Box 208
Bedford, Mass. 01730
USA

MEMBERS

Mr James P.Andersen
Director, Office of Air and Marine Systems
Transportation Systems Center
Department of Transportation
Kendall Square
Cambridge, Mass. 02142
USA

Mr Roger Voles
Chief Scientist
EMI Electronics Ltd
135 Blyth Road
Hayes, Middlesex UB3 1BP
UK

Mr l'Ingénieur Principal Chadeau
Service Technique de l'Aéronautique
4, Avenue de la Porte d'Issy
75015 Paris
France

Mr P.Sepp
IABG (Abt. WTS)
Einsteinstrasse 20
8012 Ottobrunn
Germany

Mr L.L.Gutman
Air Force Avionics Laboratory
Wright-Patterson AFB, Ohio 45433
USA

Mr G.P.Langelier
Department Head
The MITRE Corporation
P.O. Box 208
Bedford, Mass. 01730
USA

Dr S.Starr
Institute for Defense Analysis (IDA)
400 Army-Navy Drive
Arlington, VA 22202
USA

AVIONICS PANEL

CHAIRMAN: Ir. H.A.T.Timmers
NLR
Netherlands

DEPUTY CHAIRMAN: Dr M.Vogel
DFVLR, e.v.
Germany

HOST COORDINATOR

Mr Yves Brault
THOMSON-CSF
178, Bd Gabriel Péri
92240 Malakoff, France

PANEL EXECUTIVE

Lt Col. John B.Catiller
AGARD/NATO

CONTENTS

TECHNICAL PREFACE

The 38th Technical Meeting of the Avionics Panel of AGARD was held in Paris, France, 15-19 October 1979. The theme of the meeting was "Modeling and Simulation of Avionics Systems and Command, Control, and Communications Systems." Forty papers were presented in six sessions. The program included tutorials on simulation languages, validation methods, and computer representation of human decisionmaking; descriptions of large-scale command and control and air defense simulations; and new techniques in communications, avionics, and flight simulation. A number of case study applications were presented, including a complete series on uses of simulation in the development programs for large airborne surveillance systems.

Several important issues emerged from the meeting. I have tried to set them down in a reasonable order, although they seem to be somewhat interdependent.

Programming Languages

By actual count at the meeting, the favorite by far is still FORTRAN; applications of event-based general-purpose simulation languages such as GASP, SIMULA, and SIMSCRIPT to C^3 and avionics system modeling are still few and far between. One might well ask why this is so in the face of greater efficiency and ease of programming advertised for these languages. The primary reasons appear to be "transferability" and "inertia"; people who are doing C^3 and avionics system modeling tend to be more familiar and hence more comfortable with FORTRAN and can utilize each other's subroutines. The trend toward "man-in-the-loop" simulations (see below) imposes severe interrupt requirements to provide for the necessary man-computer interaction. These requirements can easily be met through FORTRAN programming; however, modification to some of the other simulation languages may be required in order to provide this capability.

General Purpose vs. Special Purpose Simulations

Very few of the papers described what might be termed general-purpose simulation tools for generic applications. To the contrary, nearly all involved special-purpose simulations which could not easily be reconfigured to represent new capabilities or to answer a new set of questions. For example, none of the air defense simulations described had the capability for explicitly representing the problem of uncertainty in aircraft identification and the resulting impact on fratricide. On the other hand the simulation described in Paper No. 28 is easily reconfigurable, and is applicable to a wide range of communications problems over a wide range of environments, communications media, and systems approaches. Such a "building block" simulation is sorely needed for command and control.

Limits to Large-Scale Models

We seem to be approaching some sort of practical limit to the utility of what might be called the centralized or monolithic model; i.e., one which is totally self-contained in a single computer program on a single computer. Several of the papers on C^3 systems, especially those in Sessions I and II dealing with command and control for air defense, suggest an approach to this limit in one form or another: The greater the complexity of the model, the greater the difficulty in understanding the model and the results, the greater the run time, and the greater the difficulty of verification, validation, and configuration control. Higher-speed, larger-memory computers and novel use of graphic displays for input and output assistance and analysis may provide only minor and temporary extensions of this limit. These concerns lead to the concept of a "distributed model." Paper No. 32 described such an approach, in which a number of separate processors are programmed to simulate specific C^3 and/or avionics functions. This arrangement permits each "submodel" to be separately validated and verified, and for the submodel interactions to be similarly tested. Timing, sequencing and protocol problems are being handled by bus techniques as in current actual distributed systems, but there are some problems. This concept of a "distributed model," if successful, would be useful in distributing the model-development load; separate groups or organizations could more easily cooperate in building and improving various parts of the model, requiring only that certain interoperability standards be rigidly followed. Finally, such a model might help stimulate research into such questions as the comparative survivability of distributed C^3 systems.

Application of Experimental Design Methods to Reduce Simulation Runs

During the meeting it was pointed out that a simulation involving 100 variables and only 2 values of each variable would require 2^{100} runs and several centuries for an exhaustive search of the "simulation space." But social scientists for decades have been dealing with this need to collapse the measurement problem and have developed very powerful sampling techniques (e.g., Latin Square design) for this purpose. Yet these methods apparently are almost unknown in the world of simulation.

Man-in-the-Loop Simulations

Existing simulations appear to have high resolution and validity in simulating the "control" side of command and control but low resolution and validity in representing the "command" side. Perhaps this is so because we do not fully understand human activities in C^3 systems, especially the decisionmaking processes involved in such functions as intelligence correlation and fusion, apportionment, allocation, assignment, and targeting (see below). For this reason we seem to be returning to a man-in-the-loop approach to simulation of C^3 systems. Such an approach involves a cycle of activities (including simulated battles) which take place in speeded-time followed by a period during which time is "stopped" and information made available to a human for decision purposes. The decisionmaker then develops or selects

an action, arranges for its execution, and the cycle repeats. This approach is gaining advocacy both in the United States and in Europe. It will certainly facilitate the study of decisionmaking in command and control; indeed, such facility may well be the most significant result of these efforts.

Human Decisionmaking

By far the liveliest and longest discussion of the symposium centered around the subject of representing human though processes in command and control. This discussion, stimulated by Paper No. 5, brought out several key issues:

- Alternative C^3 System architectures result in alternative partitionings of C^3 functions, possibly with associated differences in decision effectiveness.
- Since decisionmaking in C^3 systems tends to be distributed, some architectures may improve decision performance and others may make it worse.
- Desirability of centralization at higher levels vs. increased delegation to lower levels and associated questions of C^3 system design to support one or the other approach cannot be answered without a better understanding of the decision process itself.
- To develop such an understanding, total system simulation is required. This must incorporate a high fidelity combat environment to "drive" the cognitive processes, and either actual man-in-the-loop or simulated representations of human decisionmaking using decision logic and/or artificial intelligence techniques.
- Man-in-the-loop studies are required to identify protocols and decision algorithms for simulation by computer.

The way in which these issues are addressed over the next few years will almost certainly have a major impact on future command, control, communications and avionics systems development.

Recommendation

In summary, the meeting provided an excellent forum for interested nations to exchange information on the current state-of-the-art in modeling and simulation of avionics systems and command, control and communications systems. In recognition of the emerging issues noted above, it is recommended that another similar meeting be held in 2 or 3 years. While many of the concepts discussed in this meeting will have been further developed, simulation and modeling in areas such as new systems architecture concepts, command and control for cruise missiles, and high-density air/land battle management may provide new topics for discussion.

Command and Control Simulation - A Common Thread

Keynote Address
38th Technical Meeting of the Avionics Panel
Advisory Group for Aerospace Research and Development
Paris, France
15-19 October, 1979

by

Major General Jasper A. Welch, Jr
Assistant Chief of Staff, Studies and Analyses
Headquarters United States Air Force

Introduction

Last Spring, Joe Wohl asked that I provide a few opening remarks for this 38th technical meeting of the Avionics Panel. I'm delighted at this opportunity to share a few thoughts about a very complex subject. Over the last several years in dealing with the study of avionics issues and command, control, communications (C^3) issues, we have proved the old statement about complex problems. That is, for every complex problem there exists a solution which is simple, neat, and wrong!

Understanding and assessing the worth of military avionics systems and C^3 systems have proved to be very demanding tasks for both analysts and those who make budgetary decisions. The growing complexity of these systems continues to increase this challenge day by day.

The really frustrating aspect of avionics systems and C^3 systems is that we often don't know how to define the problem. Reasoned and well-meaning people simply don't know how to recognize military worth in such systems. With a weapon system (such as an F-15, Jaguar, or Mirage F-1), we can obtain a sense of what it is worth, for example, by observing how well it delivers ordnance or duels with enemy aircraft. Such is not the case with an avionics system or C^3 system.

If we observe that a C^3 system stores a bit of data or transmits a certain message, we really can't say much about military worth until we know a couple of additional things. We need to know how the pilot or tactical decisionmaker is likely to use the data provided by the C^3 system. And we need to know what difference this is likely to make in the combat situation.

It is to questions like "how are avionics systems and C^3 systems used?", and "what difference do they make?" that I would like to return in a moment. For the present, let me say something about the theme of this 38th technical meeting.

Theme of the 38th Technical Meeting

As mentioned in the announcement, the theme of this technical meeting concerns simulation techniques and their applications to the study of avionics systems and C^3 systems associated with airborne operations. Now many people look upon simulation models as a collection of mathematical statements and computer science techniques arranged so as to provide quantitative answers to complex problems. As any model developer can tell you, the situation is not quite that simple.

I tend to view simulation modeling in a much more philosophical sense, that is, as a systematic framework for analysis. Simulation modeling provides a unifying conceptual structure for discussing and investigating a given issue. Simulation modeling provides us with a common abstraction of the real-world situation and a common lexicon of terms with which to debate issues and exchange ideas.

The role of simulation modeling as a conceptual framework or common lexicon takes on special significance for avionics systems and C^3 systems. In 1978, the U.S. Defense Science Board Task Force on Command and Control Systems Management recognized the complexity of such systems, but also noted that the military has no commonly understood vocabulary or conceptual framework for analyzing, debating, or evaluating C^3 systems. Other conferences held on this subject have arrived at essentially the same thought, that we lack a common understanding of how avionics systems and C^3 systems contribute to military force effectiveness.

Hence, I view our meeting here this week with special interest. In holding a meeting on the simulation of avionics systems and C^3 systems, we are discussing more than just mathematical techniques and computer languages. In essence, we are discussing the framework within which each of us views command and control (or battle-management) problems and competing solutions. We are each presenting what we believe to be important aspects of command and control and what determines the contribution of command and control to military force effectiveness.

Viewed in this light, I'm sure we'll find the next several days both interesting and informative.

Now, having set the philosophical stage for simulation modeling, let me say a few words about our own views within Air Force Studies and Analyses. First, I will return to the questions of "how are avionics systems and C^3 systems used?", and "what difference do they make?" and discuss what it is that we expect from our own simulation models. What one expects from a simulation model should be uppermost in every model-developer's thoughts.

Second, I will briefly outline the hierarchical approach we have taken in organizing our various simulation models within Air Force Studies and Analyses. This hierarchical approach is dictated by some very practical considerations. However, it also turns out to be a useful way of establishing the common conceptual framework I mentioned earlier.

System Efficiency Versus Military Worth

Avionics systems and C^3 systems, like any other military system, must be justified in terms of their contribution to force effectiveness. The increasing cost of many avionics systems and C^3 systems in contrast to our constrained defense budgets has forced us to distinguish between "nice-to-have" and "essential" systems. But what are we looking for?

In a talk that I gave to the Military Operations Research Society back in 1977, I asked how one would recognize a perfect avionics system or C^3 system. The criteria stated then (which I still believe holds true) were as follows:

Preserving the order and cohesiveness of your own forces, against the forces of chaos, is the first criterion. Cohesiveness is the prerequisite to survival and to all other activities. The natural tendency of any combat force is to diffuse into uncoordinated inaction.

S.L.A. Marshall, a noted military historian, writes in his book, "Men Against Fire", about the problem of maintaining cohesion among advancing infantry troops during the Pacific fighting of World War II. Whenever the advancing infantry line came under fire, a resulting delay of 45 to 60 minutes occurred before the advance could be reorganized.

As it turned out, the delay was caused by the men seeking ground cover and losing eyesight of one another. While erect, these men had eye contact with their flanks ... a situation which allowed them to sense the unity and movement of their squad. Dropping to the ground, the men unexpectedly lost this sense of unity and awareness and could only slowly regain it by restoring interpersonal contact.

More recently, the Israelis in the 1973 war cited the location of their own troops as the most serious problem in target acquisition, command and control, and reconnaissance.

Avoiding blunders and insuring freedom of action is the second criterion, if one is to prevent situations from which there is no subsequent recovery. Blunder must be avoided in order to maintain the ability to fight at the time and place of the commander's choosing.

In the American Civil War, the Battle of Chickamauga provides us with an illustration of this point. An order for a Union division to advance into the front line was lost during its transmittal. Instead, the Union division waited in reserve. Unfortunately for the Union side, that gap in the front line turned out to be directly on the main axis of the Confederate attack. The Union army did not gracefully recover from this blunder.

During World War II, Lieutenant General Bayerlein, command of Panzer Lehr Division, mistakenly interpreted a favorable situation at the Battle of Bastogne. Hearing heavy fire on his left flank near the village of Wardin, he assumed that the fire was coming from American forces just entering the village. In actuality, the fire was coming from his own reconnaissance battalion which had nearly destroyed and scattered an American company in the village. His erroneous conclusion, based on sketchy information, caused him to prepare his forces for withdrawal and to recommend a suspension of the attack on Bastogne ... just at the time when conditions were favorable to the German forces.

The third criterion is insuring non-zero effectiveness of your own combat forces. A non-zero effectiveness is essential to winning, as opposed to the first two criteria, which are prerequisites for avoiding defeat.

We can illustrate this criterion with a Napoleonic example. He endeavored in all cases to find a favorable place and time for battle. He made a massive commitment with little subsequent effort to fine-tune or optimize the attack. He won most of the time.

Returning to S.L.A. Marshall, he found that even in the most heroic of instances, no more than a small fraction of the engaged infantrymen fired their weapons ... typically on the order of 20 - 25 percent. This astounding figure points out that even with extensive training and combat experience, the major problem for an infantry commander is to get his men to take an active part in the battle.

Optimization, or insuring efficiency, of force effectiveness ranks no higher than 4th place. Probably, it ranks closer to 17th place in the list of C^3 system criteria. In a sense, this relative emphasis is unfortunate for those of us engaged in classical operations research and systems analysis. In these fields, we have become used to thinking in terms of optimization, efficiency, and marginal return. That is, we expect to deal with functions which behave in a smooth, continuous manner. These terms, however, are somewhat inappropriate when dealing with uncertainty, two-sided force capabilities, enemy intentions, jamming, deception, and so forth. Real battles, it turns out, are rarely conducted according to narrowly constrained rules or won by small margins.

Instead of producing a nice, smooth marginal increase in force effectiveness, the addition of a new avionics system or C^3 system may result in a quantum jump from zero force effectiveness ... the result of avoiding a blunder or maintaining force cohesion at a critical instance. On the other hand, the addition of a new avionics system or C^3 system may not guarantee any force effectiveness improvement at all. The reason for this is because many command and control issues involve situational and conceptual, as well as technical, aspects. That is, the contribution of an avionics system or C^3 system depends upon three ingredients:

> System performance - What can the avionics system or C^3 system provide in terms of combat information, message transmittal rates, and so forth?
>
> Exploitation opportunities - Given the two-sided nature of combat, what opportunities exist for the tactical decisionmaker to influence events or avoid mistakes?

Decision performance - Can the tactical decisionmaker utilize the avionics system or C^3 system to assist in recognizing, exploiting, and creating such opportunities?

While performance is of direct interest to the system developer, the other two ingredients play an essential role in determining military worth. The second ingredient (exploitation opportunities) relates to the earlier question of "what difference does it make?", while the third ingredient (decision performance) relates to "how is the system used?".

Put another way, an avionics system or C^3 system deals in information. And information is information only if it (1) resolves a real ambiguity and (2) something can be done about it.

So here I have identified the three key questions to ack in the analysis of avionics systems and C^3 systems:

What can the system provide?

Where can the system make a difference?

How must the system be used to make that difference?

I should mention at this point that these questions can be asked at any system or organizational level. They apply equally to an avionics subsystem for a fighter aircraft as well as to a theater-level air defense control system. The point here is that we simply must try to get the best military worth return for our defense expenditures ... throughout the entire spectrum of avionics systems and C^3 systems. A proposed system which doesn't meet the test of the "what", "where", and "how" questions is not affordable in these days of constrained defense budgets.

Now it turns out that answering these questions in any meaningful sort of way can be a rather difficult job. In justifying the acquisition of a new avionics system or C^3 system, the analyst is attempting to build a story which relates the capabilities of the new system to some improvement in force effectiveness. Hence, we turn to simulation models which involve some portrayal of combat operations. But, then one asks "force effectiveness at what level of combat?" One-on-one? Many-on-many? Single mission? Total force?

The interdependency of weapon systems, avionics systems, and C^3 systems, plus the need to make meaningful system trade-offs, lead the analyst to seek answers at higher and more encompassing levels of combat operations. Correspondingly, the analytical tools employed for these analyses have grown in both scope and detail. I have seen this type of growth in our own combat simulation models as more force components and mission areas are added to increase the robustness of the particular methodologies.

Unfortunately, we eventually reach a practical limit on the size of our simulation programs ... due either to the storage capacity of our digital computers or to the time it takes to extract meaningful results.

To illustrate, assume for the moment that we have constructed a large (say, theater-level) simulation program capable of reflecting a moderate amount of detail about a two-sided conflict situation. Further assume that this simulation program accepts on the order of 100 input parameters.

Now, being prudent analysts, we wish to understand the sensitivity of this model to changes in these various input parameters. With a minimum of two values for each input parameter, we would require 2^{100} or about 10^{30} runs of the simulation program. Consider further that our simulation model is very fast ... on the order of nanoseconds, with a processing time of 10^{-9} seconds. Even with a fast model, it would take us 10^{21} seconds, or about 10^{11} centuries to complete our simple sensitivity analysis.

The point of this overly simplified illustration is that large simulation models are not always very practical to build and employ. One runs the danger of spending too much time attempting to understand the behavior of the model ... with little confidence that its important features have been verified. Additionally, large simulation models force the analyst to accept the results on a take-it-or-leave-it basis. Little opportunity is provided for the analyst to step-wise build up confidence with intermediate results.

Within Air Force Studies and Analyses, we have chosen to deal with this situation by organizing our simulation models in hierarchical fashion. The advantage of hierarchical models is easy to see from my original example. Suppose we are able to take our original simulation program and break it down into a hierarchical set of 10 models, each accounting for 10 of the original 100 input parameters.

Now, for each new model we have $2^{10} = 1024$ runs of the program to complete its sensitivity testing. For the set of 10 models, we have $10 \times 2^{10} = 10,240$ runs ... quite a gain in efficiency over the 10^{30} runs required with our single model. With a hierarchy of 20 models, each accounting for 5 of the original input parameters, the gain is even greater with only 640 runs required.

To illustrate one such hierarchy, consider air defense operations for a moment. At the bottom level of this hierarchy, we employ simulation models which address one-on-one combat engagements. For fighter-versus-fighter engagements, we have a model which simulates one-on-one duels using a standard repertoire of aerial tactics for each aircraft. A detailed post-processor computes the expected results of gun firings or missile launches for each firing opportunity.

For surface-to-air defenses, we have a family of one-on-one attrition models. These models simulate the detailed kinetics of single missile launches and gun firings. Example effects portrayed at this level of simulation include the impact of countermeasures, imperfect tracking information, and aircraft speed, altitude, and maneuver.

Moving up the hierarchy, we employ more aggregated models to integrate several weapon systems simultaneously. For fighter-versus-fighter operations, we are developing a simulation model for few-on-few engagements. This model addresses the coordination of tactics which occurs among different aircraft in the same flight unit.

For surface defenses, we have another model which simulates an array of defense units. Issues addressed by this simulation model begin to take on a more complex nature involving threat prioritization, fire distribution, defense suppression, and so forth.

At the next level in the air defense hierarchy, we are developing a model which addresses integrated ground defenses and fighter operations. Here we are developing the model as a top-down modular structure of event-processors. The simulation includes detailed command and control logic for integrating a variety of related missions and activities under a stressed environment.

At the highest level, we examine theater-level operations using a more aggregated modeling approach. Here, offensive and defensive air operations are portrayed in an attempt to gain a sense of the entire theater air war. However, some detail is lost as the simulation is based on the use of Markov state transition processes.

As I mentioned before, we turned to the hierarchical approach for basically practical reasons ... that is, not wanting to spend 10^{11} centuries waiting for answers. As we developed our model hierarchies, however, we began to discover that they provided a useful way of organizing our thinking about problems.

Now, looking through the planned agenda for this week, I noticed that the various papers correspond in a sense to a similar type of hierarchy. We start off with theater-level system simulation and gradually work our way down to subsystem simulation.

Accordingly, I thought it might be appropriate to spend the remainder of this time discussing a few of the lessons we've learned with using hierarchical models. These observations might be particularly useful later this week as we listen to the various perspectives on avionics systems and C^3 systems and attempt to construct a common framework for analysis.

Simulation Models - Hierarchy and Consistency

Nc aside from the practical reasons for wanting hierarchical models, we've found several other advantages. First, we've found that this approach provides a natural framework for organizing integrated study teams within Air Force Studies and Analyses. Focusing on a particular echelon or mission area allows us the opportunity to effectively combine analytical and operational talent into a cohesive study group. This group becomes our critical mass for innovative analysis.

For command and control problems, this approach is critical to achieving a well-developed understanding of the "what", "where", and "how" questions posed earlier. Answers to these questions require a lot of good, imaginative thinking about the requirements of combat and the potential for improving force effectiveness. We've found that focusing small integrated groups on specific aspects of a command and control problem succeeds best. For example, Air Force Studies and Analyses has one study team devoted to defense suppression, another to offensive air support, and yet another to higher echelon C^3 issues.

A second advantage of hierachical models is that we are able to provide short-term answers to command and control problems while waiting for more complex models to be built. One-on-one or few-on-few situations may be examined in detail by lower level models in the hierarchy. Thus, we are able to step-wise build up confidence in these models before integrating their results into more complex analyses.

Both of these advantages are just reflections of good analytical approach. That is, we must address any complex problem like command and control by breaking it down into understandable components. The notion of a hierarchy of models is naturally consistent with this procedure.

For example, in relating C^3 capabilities to an improvement in force effectiveness, one might address a hierarchy of effectiveness measures. At the bottom of the hierarchy, we might be interested in "single-engagement probability-of-kill". Moving upward in the hierarchy, one might address "single-mission effectiveness" or "single-raid effectiveness". Eventually, one could relate C^3 capabilities to improvements in theater-level effectiveness by addressing "5-day air campaign results".

A hierarchy of this type allows one not only to relate military objectives to one another, but also to construct an explicit accounting of how avionics or C^3 systems contribute to fulfilling these objectives. Moving upward in the hierarchy of effectiveness measures, one can ask "why is it important to achieve a lower-level military objective?" Moving downward in the hierarchy allows one to ask "what detailed objectives must be met in order to achieve this overall measure of force effectiveness?"

Similarly for avionics systems and C^3 systems, one may ask "why is it important that a specific data rate or type of information be provided at a given command echelon?" Or, conversely, "what lower-echelon command and control capability must be provided and integrated to permit the successful completion of some overall plan or operation?"

Thus, we have found that hierarchical models provide us with a structured approach to analysis. By proceeding one step at a time, we are able to relate avionics system and C^3 system capabilities to force effectiveness in a logical manner.

Now I must point out that there is still a substantial degree of "art" associated with deciding where and how to break down a problem into a set of hierarchical models. Many problems can arise and most of these problems have something to do with insuring consistency among model results.

The nature of this problem is easy to see from my example discussed earlier. Recalling our original simulation model with 100 input parameters, I noted that about 10^{30} runs are needed to perform a full sensitivity analysis. With 10 models, about 10,640 runs are required. With 20 models, only about 640 runs are needed.

This gain in efficiency does not come free, however. By breaking down our one large simulation model into several smaller models, we have lost the capability to explicitly represent the interactions occurring between each subset of input parameters. Now, if we had the ideal situation, we might be able to select subsets which were nearly independent of one another. Thus, we could run each of our hierarchical models and not worry too much about their results being incongruous or incompatible.

Unfortunately, we can not always insure that our different models are independent of one another. Often, we find rather strong interdependencies existing among different models in a hierarchy. Hence, we must worry about consistency!

There are two basic criteria associated with consistency. First, we must insure that model parameters essentially mean the same things in different simulation models. That is, the definition and surrounding assumptions for parameters output from one model must be consistent with the manner in which they are used as input to another model. Secondly, the behavior of model parameters must be consistent. That is, we must insure parameter continuity in a calculus sense ... a consistency among derivatives of the 1st order, 2nd order, and so forth.

To insure that both criteria are met as well as possible, we have found it desirable to overlap simulation models. That is, we purposely duplicate certain operations and detail in two or more models. This allows us the opportunity to check first-hand on whether or not parameter definitions and behavior are being contradicted.

Returning to the analysis of avionics systems and C^3 systems, we have found the concern for model consistency to be particularly great. Here, we must insure consistency for each of the "what", "where", and "how" questions posed during the analysis.

Problems of consistency involve the technical performance of a given avionics system or C^3 system, the tactics and procedures by which the systems are employed, and the likely environment in which they are expected to contribute to force effectiveness. Assumptions which seem reasonable at one level of analysis must be enforceable at another. For example, if we assume a certain message loading rate while analyzing the detailed performance of a communications system, we need to insure that this message loading rate is representative of the total number of users involved.

Insuring consistency can become particularly troublesome when several different missions are combined into a higher level analysis. In examining the details of one mission area (say, offensive air support) there is a tendency to ignore critical conditions which must be met for other mission areas (such as air defense). Airspace management and the competing requirements for air defense and safe passage of friendly offensive aircraft are good examples of this type of concern.

Now I've been concerned with this problem for some time. Within Air Force Studies and Analyses, we conduct seminars where our analysts get together in an attempt to achieve some degree of model consistency and configuration control. I even have a special staff office charged with the responsibility of thinking about this general problem.

With our increasing interest in avionics and C^3 issues, we've found that model consistency requires even more attention. The subtle synergism existing among technical performance, the combat environment, and how the systems are used provides a lot of opportunity for model divergence, if not properly monitored. Indeed, the U.S. Defense Science Board's comment on the lack of a commonly understood vocabulary or conceptual framework says a lot about the magnitude of this problem.

Hence, the charge I would like to leave you with this week is one of insuring consistency ... consistency of models and consistency of analyses. We must insure that our detailed analyses of avionics systems and C^3 systems are logical extensions of our more aggregated studies. We must focus on our own particular subsystems and issues, but we must also maintain a general awareness of the overall environment in which these subsystems operate. We must begin to build the common vocabulary and conceptual framework for avionics and C^3 analysis. And, above all, we must provide our forces with avionics systems and C^3 systems attuned to real-world needs.

AN INTRODUCTION TO THE SELECTION AND USE OF SIMULATION LANGUAGES*

Robert G. Sargent
Department of Industrial Engineering and Operations Research
441 Link Hall, Syracuse University
Syracuse, New York, 13210, U.S.A.

SUMMARY

This paper contains an introduction to the selection and use of simulation languages for digital computers. The topics discussed are the hierarchy of computer languages and their relationship to simulation, the advantages and disadvantages of using simulation languages, the factors to consider in selecting simulation languages for an organization and a language for solving a specific problem, some characteristics of the simulation languages GASP, GPSS, SIMSCRIPT, SIMULA, and SLAM, and future developments in simulation languages. The emphasis is on discrete and combined simulation languages.

1. INTRODUCTION

One of the time consuming steps in a simulation study is the translation of the defined flowchart model into a computer program to be run on a digital computer. There are several different types of computer languages that can be used, each with their own strengths and weaknesses. The purpose of this paper is to provide an introduction into selecting and using a language for performing this step in a simulation study. The language should be selected prior to developing the flowchart model because there must be a compatibility between how the system is modelled and the computer language used. More thorough general treatments of simulation languages and their use can be found in Emshoff et al, 1970, Fishman, 1978, Gordon, 1977, Korn et al., 1978, Pritsker et al., 1979, and Shannon, 1975.

2. HIERARCHY OF COMPUTER LANGUAGES

The digital computer operates in a language called machine language which consists of 0's and 1's. We do not program in this language due to its complexity. The next level of computer languages is assembly languages and they are usually machine dependent. Programs are written in assembly language only if they are to be used over and over again because the programming effort required is considerable. Analysts almost never used assembly language to program simulation models.

The next level of computer languages is general purpose or higher level languages. They are user oriented and are usually machine independent. Machine independent means that if an application program is written in one of these languages, that program will generally run on any computer having that language. General purpose languages are either compiler or interpreter languages. A compiler language uses a compiler to convert application programs into machine language or into assembly language for conversion to machine language. This compiling (conversion) takes a certain amount of computer time. The computer then "executes" the resulting machine program.

In interpreter languages, each line of the application program is converted to machine language each time it is executed. This means that if a line of an application program is used several times, it must be converted to machine language each time. Interpretive languages generally require more computer time for discrete event simulation than compiler languages because a considerable portion of discrete event simulation programs are used over and over again.

General purpose languages are frequently used in programming simulation models and is the implementation language of several simulation languages. FORTRAN is the general purpose language most used for simulation in the United States and is also the implementation language of the GASP and SLAM simulation languages. Examples of these languages are given in Table 1.

The next level of computer languages are problem or application oriented in addition to being user oriented. Simulation languages belong to this level of languages. Beginning in the late 1950's and earlier 1960's, different groups of individuals performing simulations recognized that several of the same functions were used in almost every simulation and they therefore could be programmed into subroutines and "tied" together to be used for future simulations. From these special programs (languages, if you wish), simulation languages have evolved until today we have commercially available several general and special purpose simulation languages, including some extremely sophisticated ones. Several examples are given in Table 1.

General purpose simulation languages can be broken into three general classes: discrete, continuous, and combined (discrete/continuous). Discrete simulation languages are for programming discrete event simulation models, i.e., simulation models whose "states" (variables) change at specific points in time. Continuous simulation languages are for models whose variables (states) change continuously over time. Combined languages are of recent development and provide the capability of allowing models to have variables that may change discretely, continuously, and continuous with discrete jumps.

Special purpose simulation languages are simulation languages that have been developed for modelling and simulating specific types of systems. Specialized simulation languages for simulating computer systems are examples of these languages. Many of the special purpose simulation languages have evolved from general purpose simulation languages. Some examples are contained in Table 1. Both general purpose and special purpose simulation languages are widely used.

The remainder of this paper, unless otherwise stated, will be restricted to discrete and combined simulation.

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* This paper is based on "Introduction to Simulation Languages," by Sargent, Robert G., contained in the Proceedings of the 1978 Winter Simulation Conference.

TABLE 1

HIERARCHY OF COMPUTER LANGUAGES WITH EXAMPLES

Machine Languages

Assembly Languages
  BAL, MACRO 10

General Purpose Languages
  Compiler:
    ALGOL, BASIC, COBOL, FORTRAN, PL/1

  Interpreter:
    APL, LISP

Simulation Languages
  General Purpose
    Discrete:
      ECSL, GASP, GPSS, MILTRAN, SIMSCRIPT, SIMPL/1, SIMULA, SLAM
    Continuous:
      CSMP, DARE, DYNAMO, MIDAS, MIMIC
    Combined: (Discrete/Continuous)
      C-SIMSCRIPT, GASP IV, SLAM

  Special Purpose:
    CSS II, ECSS II, Q-GERT

3. WHY SIMULATION LANGUAGES

The major advantage of using simulation languages over other languages is the reduction in programming time required to program the model. This is extremely important as it allows the analyst performing the simulation study to devote more time to other phases of the study. In addition, most simulation languages provide conceptual guidance, modelling capability, and aid in communication and documentation.

The disadvantages of using simulation languages are (i) the cost of obtaining and maintaining them, (ii) the time analysts must spend learning the simulation languages they plan to use, and (iii) the increased computer storage and computations time required in using them beyond what is needed in using a general purpose language.

Simulation languages generally provide at least the following:

(a) World View
(b) Time Flow Mechanism (Advance time and keep a list of future events)
(c) Random Number Generator
(d) Random Variate Generators
(e) Model Data Collection Capabilities
(f) Perform Elementary Statistical Analysis on Collected Data
(g) Provide Error Diagnostics

4. SELECTION OF A LANGUAGE

There are two different levels in selecting languages for simulation. The first level is concerned with what languages should be available for simulation in a given organization. The second level is what language should an analyst use in a specific simulation study.

Some of the factors that need to be considered in selecting languages for an organization are:

(1) Language compatibility with organization's computer system;
(2) Language adequately supported;
(3) Language suitable for problems that likely will be simulated;
(4) What are the costs to obtain, install, maintain, and update the language;
(5) Effort required to learn the language;
(6) Documentation on language;
(7) Ease of using language;
(8) Language computer time efficiency;
(9) Language storage requirements;
(10) Language flexibility;
(11) Language capability, including error diagnostics, modelling capability, data analysis, etc.;
(12) Will use of the language justify its cost.

In selecting a language for a specific problem the analyst generally considers at least the following:

(1) What is available, either inhouse or commercially available elsewhere such as on time sharing systems.
(2) What languages does the analyst know.
(3) What type of problem does the analyst have.
(4) What are the language capabilities including:
  (a) which world view: event, activity, or process;
  (b) problem compatibility;
  (c) data collection and data analysis;

(d) ability to expand model, if necessary;
(e) generation of random numbers and variates;
(f) error diagnostics and documentation;
(g) communication ability, particular to user of model's results;
(h) code self documentation;
(i) report capabilities.

(5) Programming effort required
(6) Computer time required.
(7) Computer storage required.
(8) Portability of model, if required.

The analyst is generally able to quickly reduce the choice of a language down to at most one special purpose simulation language, one or two general purpose simulation languages, and one or two general purpose languages. The analyst then will usually choose the language requiring the least programming effort provided it will allow flexibility to expand the model in the future, if it should ever need it, and the computer and storage time required to use that language is reasonable.

In selecting simulation languages for an organization or a language for a specific problem, one should know that those languages that require a longer learning time generally have greater capability than those requiring a shorter learning time. One should also be aware that the simulation languages having the event world view usually require a larger programming effort than those having the process world view. However, they generally allow more control and flexibility in modelling and in model data collection than the other world views.

5. SOME SPECIFIC SIMULATION LANGUAGES

There are numerous general and special purpose simulation languages available today. For a variety of reasons, most have not become popular. As an example, Oren, 1977, list eighteen combined simulation languages but only one of these eighteen have ever been widely used.

The most popular discrete general purpose simulation languages today are GASP, GPSS, SIMSCRIPT, and SIMULA. These languages were born in the early 1960's and they continue to evolve. Each have their own strengths and weaknesses. Table 2 contains some of the characteristics of the current versions of these languages and on the new general purpose simulation language SLAM. SLAM has been included because this author believes this language will become popular in the future because it contains several different discrete world views in addition to having continuous and combined (discrete/continuous) modelling capability. References on each of these languages can be found in the Bibliography by using Table 2.

TABLE 2

CHARACTERISTICS OF SOME SIMULATION LANGUAGES

Characteristic					
Language Name	GASP	GPSS	SIMSCRIPT	SIMULA	SLAM
Meaning of Name	General Activity Simulation Program	General Purpose Simulation System	No specific meaning	No specific meaning	Simulation Language for Alternative Modelling
Current Versions	GASP II (Discrete), GASP IV and GASP_PL/1 (Discrete, Continuous, and Combined)	GPSS/360, GPSS V, GPSS/H and several others (all Discrete)	Simscript II.5 (Discrete), C-Simscript, (Disctete, Continuous and Combined)	SIMULA 67 (Discrete)	SLAM (Discrete, Continuous, and Combined)
Implementation Language	FORTRAN or PL/1	Assembly	Machine	ALGOL	FORTRAN
Computer System	Any computer having a FORTRAN or PL/1 compiler (some commercial time-sharing systems)	Most large computers (several commercial time-sharing systems)	Most large computers (several commercial time-sharing systems)	Most large computers	Any computer having a FORTRAN compiler (some commercial time-sharing systems)
Language Orientation	Statement	Block	Statement	Statement	Statement or Network
World View (Discrete)	Event	Process (transaction)	Event or Process	Process	Event and Process
Storage Management	Fixed	Dyanmic	Dynamic	Dynamic	Fixed
Language Type	Compiler	Interpreter (GPSS/H: Compiler)	Compiler	Compiler	Subprogram Library / Compiler
Language Purchase Cost	Inexpensive	Moderate	Moderate	Moderately Expensive	Inexpensive
References	[14, 15, 16]	[2, 6, 8, 23]	[3, 20, 21]	[1, 9]	[18]

6. FUTURE DEVELOPMENTS

Simulation languages have been evolving since the early 1960's and this trend should continue into the foreseeable future. Some of the simulation language developments expected in the near future are (i) increased modelling capability provided directly in the languages such as that provided by the new language SLAM, (ii) options for model data collection and statistical analysis provided directly in the languages, (iii) languages having interactive capability for programming, debugging, and model analysis, (iv) languages using computer graphics for modelling, programming, validation, and analysis, (v) languages for minicomputers, (vi) reduced computation (model run) time due to improvements in the languages themselves, e.g., more efficient future event set algorithms (McCormack, et al., 1979), and (vii) increased number of special purpose simulation languages.

7. CONCLUSIONS

As systems become larger, more complex, and costlier, the use of modelling will increase, in particular the use of simulation modelling. A large percentage of simulation models developed today use a simulation language and this percentage will increase as the capabilities of the simulation languages continue to evolve. This paper provided an introduction to the selection and use of languages for simulation.

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AN INTRODUCTION TO STATISTICAL ANALYSIS OF SIMULATION OUTPUT DATA*

Robert G. Sargent
Department of Industrial Engineering and Operations Research
441 Link Hall, Syracuse University
Syracuse, New York, 13210, U.S.A.

SUMMARY

This paper is a tutorial paper on how to obtain point and interval estimates (confidence intervals) of means for both terminal and steady state simulations. The simple methods of replication, batch means, and regenerative cycles are presented in detail and applied to a model of a simple time-shared computer system to illustrate their use. A brief discussion is included on sequential procedures and time series methods for obtaining these estimates. The advantages and disadvantages of the various methods are given, including specific recommendations as to when certain methods might be used.

1. INTRODUCTION

The principal goal of most simulation studies is to investigate the behavior of a system. This is accomplished by developing a simulation model of the system of interest and investigating its behavior by performing either a steady state or a terminating anaysis on the model's output data (Law, 1979a). In steady state analysis, we are interested in estimating parameters whose values are constant with respect to time. This implies that the statistical properties of all of the model's variables are time invariant, i.e., stationary, after a delay of at most a short period of time determined by the model's initial conditions (state). An example of steady state analysis is determining the mean waiting time of customers in a system assuming the interarrival and service times are time invariant and steady state occurs.

In terminating analysis, we are interested in analyzing the model's behavior over a finite time period which may be of fixed or of random length. Examples of terminating analysis are (i) determining how many days it takes to fill an empty reservior assuming a random input, (ii) determining how many customers are served in a store opened from 8 to 5, (iii) determining the length of time a new system operates until its first failure, (iv) determining the expected change in the gross national product between 1979 and 1989, and (v) determining the affect of a five percentage yearly harvest of whales between 1980 and 2050. In terminating simulations the results are a function of the state of the model at the beginning of the finite time period (model's initial conditions) of interest.

The minimum statistical analysis that should be performed in both steady state and terminating analysis is to obtain point and interval estimates of the means of the output variables of interest. Unfortunately, a comprehensive statistical methodology for analyzing simulation output data remains to be developed. This frequently leads to simulation studies having inadequate statistical analysis performed on their output data. Far too often only point estimates of the means of the output variables are obtained without any determination of how good they are, i.e., no confidence intervals (interval estimates) are determined.

There are statistical methods of analysis that can be used to obtain both point and interval estimates of the means of simulation output variables for both steady state and terminating simulation studies. The objective of this tutorial paper is to describe the simpler methods of obtaining point and interval estimates of the means, including their advantages and disadvantages, with the hope that better statistical analysis will be performed in simulation studies.

After a simulation model has been verified and validated (Sargent, 1978 and 1979), the model is ready to have experiments performed on it to obtain a set of output observations (data) for analysis. The output observations are in general not independent but correlated, usually positively. This complicates obtaining interval estimates of the mean. Because the method of analysis commonly used for obtaining point and interval estimates of terminating simulations is one of the methods used in steady state analysis, we will restrict our discussions to steady state analysis except for Section 7.

In performing a steady state analysis, a set of initial conditions must be put into the simulation model which will usually cause the model to go through a transient response prior to reaching a steady state. (We are assuming that the model under analysis has a steady state mean.) The analyst must, in addition to determining the model's initial conditions, decide what method of data collection and data analysis to use under a constraint of a fixed number of observations because the amount of computer time is generally limited. Since the steady state observations are usually correlated, data must be collected in a way to obtain independent observations to allow classical statistics to be used or time series techniques used.

The three data collection methods used to obtain independent observations are (1) the method of replication, (2) the method of batch means (subintervals), and (3) the regenerative method. The analyst must choose one of the above three methods of data collection and use classical statistical analysis or choose one of the following time series methods: spectral analysis, autocorrelation, autoregressive, or autoregressive-moving average. Classical statistical analysis is generally used to obtain point and interval estimates of the mean because using classical statistical is easier than using time series techniques, analysts frequently are knowledgeable about classical statistics and time series techniques are sensitive to proper application and require knowledge of advanced statistics. Because of these reasons, we will describe in detail only the three methods using classical statistics.

The remainder of this paper is divided into seven sections. The next section discusses general statistics that are used in this paper. Section 3 describes the three methods of obtaining independent observations and their analyses and Section 4 applies these methods to a simulation study of a Time-Shared Computer System. Section 5 briefly discusses sequential procedures and time series methods of analysis and Section

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* This paper is an expansion of the paper "Statistical Analysis of Simulation Output Data," by Robert G. Sargent, contained in the ACM Proceedings of the 1976 Symposium on the Simulation of Computer Systems.

6 discusses selection and comparisons of the various steady state methods. Section 7 discusses analyzing terminating simulations and the last section is the conclusions.

2. GENERAL STATISTICS

Suppose we label a set of observations from a stochastic process $x_1, x_2, \ldots, x_k$. This could be, for example, k output observations from a simulation model. A point estimator of the mean μ of this stochastic process could be obtained by using the statistic (a quantity calculated from sample observations) given by (1). If the observations $x_1, x_2, \ldots, x_k$ are independent and identically distributed (iid), which we <u>will</u> assume until stated otherwise, then several additional statements can be made. First the estimator $\bar{x}$ is an unbias estimator, i.e., $E(\bar{x}) = \mu$. Secondly, an unbias point estimator of the variance of x is given by (2). Statistics, such as $\bar{x}$ and s^2, are random variables and have distributions called sampling distributions which describe their behavior. The variance of $\bar{x}$ is given by (3) and its point estimator by (4). If the variance of x is known and finite, then by the central limit theorem we have (5). In general,

$$\bar{x} = \frac{1}{k} \sum_{i=1}^{k} x_i \tag{1}$$

$$s^2 = \frac{1}{k-1} \sum_{i=1}^{k} (x_i - \bar{x})^2 \tag{2}$$

$$\sigma^2_{\bar{x}} = \frac{\sigma^2}{k} \tag{3}$$

$$s^2_{\bar{x}} = \frac{s^2}{k} \tag{4}$$

the variance of x is not known, but it can be shown that (5) continues to hold if its estimator $s^2_{\bar{x}}$ is used to replace $\sigma^2_{\bar{x}}$. Therefore, for large sample sizes, the sampling distribution of $\bar{x}$ can be approximated by a normal distribution. One generally considers sample size large if k is greater than forty (40) <u>provided</u> that the distribution of x is reasonably well behaved.

$$\lim_{k\to\infty} \mathrm{Prob}\left[\frac{\bar{x}-\mu}{\sigma_{\bar{x}}} < b\right] = \frac{1}{2\pi} \int_{\infty}^{b} e^{-y^2/2} dy \tag{5}$$

If one desires the exact sampling distribution of $\bar{x}$, then the distribution of x must be known. In this paper, we <u>will</u> assume the variance of the random variable x is unknown in discussing the sampling distribution of $\bar{x}$. If the x_i's are iid and normally distributed, then the sampling distribution of mean with k observations is the t distribution with k-1 degrees of freedom. If the x_i's are not normally distributed but can be approximated by a normal, it is common practice to use the t distribution as the sampling distribution. Unfortunately, many simulation output variables of interest have a density function that is non-negative, unimodal, and positively skewed.

Since $\bar{x}$ is a random variable, it is usually desirable in practice to determine how accurate this point estimator is. This is usually accomplished by constructing a confidence interval for μ. The confidence interval is determined by choosing two point estimators in such a way that one can state a probability that the interval contains the <u>mean</u>, a fixed but unknown quantity. In order to obtain this confidence interval, the sampling distribution of $\bar{x}$ must be known. If the sampling distribution is a t distribution, the $100(1-\gamma)$% confidence interval for μ is given by (6) where $t_{k-1,1-\gamma/2}$ is the $1-\gamma/2$ point of the t distribution with k-1 degrees of freedom. This implies that the probability that the confidence interval given by (6) contains the steady state mean is $1-\gamma$. It is also common practice to use (6) as the confidence interval of the mean if the observations are approximately normal. As k increases, the t distribution approaches

$$\bar{x} \pm s_{\bar{x}} t_{k-1,1-\gamma/2} \tag{6}$$

the normal. For large samples, one replaces $t_{k-1,1-\gamma/2}$ in (6) by the $1-\gamma/2$ point of the standard normal, $(\mu=0, \sigma^2=1)$. (A sample is generally considered large if k is greater than forty.) The t distribution is a flatter distribution than the normal and its behavior is such that it gives a larger value for $t_{k-1,1-\gamma/2}$, the smaller k is. If a more accurate estimate of $\bar{x}$ is desired, then the number of observations should be increased to reduce the variance of the sampling distribution. One should also be aware that increasing the probability that the confidence interval contains the mean causes the size of the confidence interval to increase.

As stated in Section 1, most simulation output variables go through a transient response before reaching steady state and the observations are usually positively correlated. If the transient observations are included in the analysis, this will result in $\bar{x}$ being a bias estimator of μ, the steady state mean. If the data is correlated and is analyzed as if it is independent, the point estimate of $\sigma^2_{\bar{x}}$ will be incorrect.

Since simulation data is usually positively (negatively) correlated, the variance of $\bar{x}$ will be underestimated (overestimated) resulting in a smaller (larger) confidence interval for the mean than is correct. It should be noted that most simulation languages that provide the capability of calculating variances estimators, analyze the data as if it is independent and, therefore, care should be used as to when it is appropriate to use this capability.

If the data of a simulation output is correlated and in steady state, we have what is called a covariance stationary or wide-sense stationary stochastic process. Correlation does not effect estimating the mean, but does the variance of $\bar{x}$. The autocovariances of the observations are given by (7) and their point estimators by (8). The autocorrelations are given by (9) and they lie between plus and minus one. Their

$$R_i = E(x_t - \mu)(x_{t+i} - \mu) \tag{7}$$

$$C_i = \frac{1}{k-i} \sum_{t=1}^{k-1} (x_t - \bar{x})(x_{t+i} - \bar{x}) \tag{8}$$

$$\rho(i) = \frac{R_i}{R_o} \tag{9}$$

point estimates, $\tilde{\rho}(i)$, are obtained by replacing R_i by C_i. $\rho(i)$ is usually positive for simulation output data and decreases exponentially as i increases. The estimate of the variance of $\bar{x}$ is given by (10). One notes that if $\hat{\rho}(i)$ is zero for all i, then (10) is the same as (4). One can readily see from (10) that the variance of x is underestimated (overestimated) by the values associated with the autocorrelations if the simulation data is analyzed as if it is independent and is in fact positively (negatively) correlated.

$$s^2_{\bar{x}} = \frac{s^2}{k} \left[1+2 \sum_{i=1}^{k-1} (1-\tfrac{i}{k})\hat{\rho}(i)\right] \cong C_o + \sum_{i=1}^{k-1} (1-\tfrac{i}{k})C_i \tag{10}$$

3. DESCRIPTION OF METHODS USING INDEPENDENT ANALYSIS

If the observations generated by the simulation model are iid, then the point and interval estimators described in Section 2 may be used directly for steady state means. Since simulation output observations are generally correlated, then independent observations must be obtained if classical statistics is going to be used for analysis. The three major approaches to obtaining independent observations and the desired estimators are described below. Additional information on these methods can be found in Crane et al., 1974a, 1974b, 1975a, 1975b, 1977, Fishman, 1978, Kleijnen, 1974, 1975, Law, 1977, 1979a, 1979b, and Pritskar et al., 1979.

3.1 The Method of Replication

The method of replication is defined as making k independent simulation runs (replications) of length m observations each for a total of N observations. The independence of runs is accomplished by using a different stream of random numbers for each run and the same initial conditions. Let x_{ij} be the jth observation of the i^{th} run and R_i be the average of the i^{th} run. By definition the R_i's are iid. Using the R_i's in (1) and (2), the point estimators for the steady state mean μ and the variance of the R_i's are obtained, respectively. Using the s^2 calculated by (2) in (4), $s^2_{\bar{x}}$ is obtained. The confidence interval of μ is obtained by using (6). Before using the R_i's described above to calculate point and interval estimates of the steady state mean, μ, one must consider two possible sources of error for these estimates.

If each run goes through a transient response before reaching steady state and the transient observations are included in calculating the R_i's, then $\bar{x}$ will be a bias estimator of the steady state mean μ. One must be careful of obtaining a bias in $\bar{x}$ because the confidence interval is around $\bar{x}$, particularly when k is large because the confidence interval decreases as k increases. It is, therefore, common practice to delete a fixed number of observations (the transient observations) from the beginning of each run before calculating the R_i's in order to eliminate the bias. However, as one eliminates observations in calculating the R_i's, the variance of $\bar{x}$ increases resulting in a larger confidence interval. This means that a trade-off must be made between a possible bias in $\bar{x}$ and the size of the confidence interval. The difficulty is that there is not any procedure currently known to determine how many observations to delete (Gafarian, et al., 1978, and Wilson et al., 1978a).

The second source of possible error is if the distribution of the R_i's are non-normal. This causes the sampling distribution of $\bar{x}$ not to have a t distribution and, therefore, using (6) will generally result in incorrect confidence intervals. One way to eliminate the non-normality effect is to use a large sample size (large k), bringing into effect the central limit theorem. However, this approach increases the number of transient observations which must be eliminated to avoid a bias in x. If only a fixed number of x_{ij} observations can be obtained, the fewer observations that are eliminated due to transient responses, the better, because this will result in a shorter confidence interval. Increasing m will usually cause the R_i's to approach a normal, but at a slower rate.

3.2 The Method of Batch Means

The method of batch means (subintervals) is defined as dividing one simulation run of length $N(x_1,x_2,\ldots,x_N)$ into k batches (segments) of m observations each. If we let B_i be the average of the m observations in batch i and choose m sufficiently large, then the B_i's should be essentially uncorrelated. If the B_i's are uncorrelated and are normally distributed, then they are also independent. Even if the B_i's are not normal, it is common practice to assume that they are independent if they are uncorrelated. One method used to determine if the B_i's are uncorrelated is to estimate their correlations using the formulas given in Section 2. Some recent empirical evidence (Duket, et al., 1978 and Law, 1977) has emerged that these formulas may have biases for analyzing data such that the estimates are lower than the actual values. If this is true then one may believe the B_i's are uncorrelated when in fact they are positively correlated. A more accurate method is to use the one recommended by Fishman, 1978. One notes that the method of batch means has only one transient response compared to the method of replication which has a transient response for each replication.

The point estimators $\bar{x}$ and s^2 are obtained by using the B_i's in (1) and (2). The confidence interval for μ is obtained by using (4) and (6). There are three possible sources of error in using the B_i's to calculate the point and interval estimates of the mean. If there is a transient response and the transient observations are used, then $\bar{x}$ will be a bias estimator of the steady state mean μ unless they are deleted as discussed under the method of replication. It is common practice to delete the transient observations prior to dividing the run into batches for analysis.

The second source of possible error is that the distribution of the B_i's may be non-normal. This could cause the confidence interval to be incorrect as discussed above. A large sample size (a large k) could also be used to bring the central limit theorem into effect for the sampling distribution of $\bar{x}$. This would not increase the number of transient observations as in the method of replication.

The third possible source of error is that the B_i's may be positively (negatively) correlated. If they are, the variance of $\bar{x}$ will be underestimated (overestimated) as discussed in Section 2. This would result in a smaller (larger) confidence interval than is correct. To avoid the possibility that the B_i's are uncorrelated, the size of each batch should be as large as possible (large m). For a fixed N, a trade-off must be made between the size of k and m, which may eliminate using a large sample size (large k) to enable the sampling distribution to become approximately normal if the B_i's are non-normal. One must also remember that increasing m will cause the B_i's to approach normality if the x_{ij}'s are non-normal.

3.3 The Regenerative Method

The regenerative method is defined as dividing a simulation run into a sequence of iid intervals, called cycles, by using regenerative points. A model or system is regenerative if it has at least one state in which future behavior is independent of past behavior. Each time the model enters this state, a regenerative point, it terminates a cycle and starts a new one. If this method of analysis is to be applicable, the expected time between regenerative points must be finite and the simulation model must be able to generate a large number of regenerative points because the sampling distribution is derived based on the central limit theorem. If regenerative points do not exist, this method cannot be used unless approximate regenerative techniques are appropriate (Crane, et al., 1975b, 1977).

The regenerative method provides a way of obtaining point and interval estimates of $E(f(X))$. Examples of $E(f(X))$ are $E(X)$, $E(X)^2$, and $P(X=0)$, where X can be a random variable for the steady state waiting time, steady state number in queue, steady state cost, etc. This method is more general than the two previous methods because it can obtain point and interval estimates for any $E(f(X))$.

Let us define a sequence of regenerative points (times) as $0 \leq \beta_1 < \beta_2 < \beta_3 < \ldots$. If the initial conditions are chosen such that the state of the model is at a regenerative point, no observations need be eliminated at the beginning of a simulation run; if not, then β_1 is the first regenerative point to occur in the simulation run. If more than one sequence of regenerative points occur in a simulation model, the analyst should usually choose the sequence having the largest number of cycles to hopefully obtain the best estimate (smallest confidence interval). A state that frequently creates regenerative points in an open queueing model is leaving the empty and idle state (Fishman, 1978).

For each cycle i, defined as the time interval between β_i and β_{i+1}, a Y_i and α_i must be chosen such that (11) holds. α_i is some measure of the size of the cycle, usually either the length $\alpha_i = \beta_{i+1} - \beta_i$ or a count of the number of entities data is collected on in cycle i, and Y_i is usually either a sum of the $f(X)$'s that occurred during cycle i or is found by integrating $f(X)$ over cycle i. Examples are

$$E(f(X)) = \frac{E(Y)}{E(\alpha)} \tag{11}$$

(a) $E(f(X))$ = mean waiting time, then Y_i is the sum of waiting times in cycle i and α_i is the number of entities whose waiting times are in Y_i; (b) $E(f(X))$ = mean number in queue, then Y_i is obtained by integrating the number in queue over cycle i and α_i is the length of cycle i; and (c) $E(f(X))$ = probability a server is idle, the Y_i is the length of time the server is idle during cycle i and α_i is the length of cycle i.

For k cycles, a set of observations, $Y_1, Y_2, \ldots, Y_k$ and $\alpha_1, \alpha_2, \ldots, \alpha_k$ are obtained. Since the cycles are iid, the Y_i's are iid, the α_i's are iid, and the Y_i's are usually highly correlated with the α_i's. There are several point and interval estimators that can be used for $E(f(X))$. (Please note that we must

use a ratio estimator because both the numerator and denominator are random variables.) They are a function of statistics (12) through (16). The classical point estimator of $E(f(X))$ is given by (17) and is a bias estimator. If we define the $100(1-\gamma)\%$ confidence interval of $E(f(X))$ by $r_c \pm d_c$, then the classical point estimator, d_c, is given by (19), assuming a large sample size such that sampling distribution can be

$$\bar{Y} = \frac{1}{k} \sum_{i=1}^{k} Y_i \tag{12}$$

$$\bar{\alpha} = \frac{1}{k} \sum_{i=1}^{k} \alpha_i \tag{13}$$

$$s_Y^2 = \frac{1}{k-1} \sum_{i=1}^{k} (Y_i - \bar{Y})^2 \tag{14}$$

$$s_\alpha^2 = \frac{1}{k-1} \sum_{i=1}^{k} (\alpha_i - \bar{\alpha})^2 \tag{15}$$

$$s_{Y\alpha}^2 = \frac{1}{k-1} \sum_{i=1}^{k} (Y_i - \bar{Y})(\alpha_i - \bar{\alpha}) \tag{16}$$

approximated by a normal by the use of the central limit theorem. In (19) $Z_{1-\gamma/2}$ is the $1-\gamma/2$ point of the standard normal. The Jackknife method gives better point and interval estimators of $E(f(X))$ than the classical method, in particular, for small sample sizes. The jackknife point estimator is given by (20)

$$r_c = \frac{\bar{Y}}{\bar{\alpha}} \tag{17}$$

$$s_c^2 = s_Y^2 - 2r_c\, s_\alpha^2 + r_c^2\, s_{Y\alpha}^2 \tag{18}$$

$$d_c = Z_{1-\gamma/2} s_c / (\bar{\alpha} \sqrt{k}) \tag{19}$$

and using d_j from (21), the confidence interval for μ is $r_j \pm d_j$. The classical and Jackknife estimators presented here as well as others are discussed in Inglehart, 1975. One should note that both the classical and Jackknife methods give better results than the estimators given in the original Crane and Iglehart papers (1974a, 1974b, 1975a, 1975b) and which have become widely disseminated.

$$r_j = \frac{1}{k} \sum_{i=1}^{k} \theta_i \quad \text{where} \quad \theta_i = k\, r_c - (k-1)\Big(\sum_{j \neq i} Y_j / \sum_{j \neq i} \alpha_j \Big) \tag{20}$$

$$d_j = Z_{1-\gamma/2} s_j / \sqrt{k} \quad \text{where} \quad s_j^2 = \frac{1}{k-1} \sum_{i=1}^{k} (\theta_i - r_j)^2 \tag{21}$$

There is one possible source of error in using the regenerative methods described. The sampling distribution used in developing confidence intervals for $E(f(X))$ is obtained by using the central limit theorem. Therefore, if a large sample is not used, the sampling distribution may not be a normal. One should note that the transient response is not a concern with this method. If one chooses to run a simulation for a fixed period of time, it may not end at a cycle. In this case, one uses the number of full cycles generated for data analysis and neglects the portion of a cycle left at the end of the run.

4. A CASE STUDY

Let us apply the data anlysis techniques presented in Section 3 to simple time-shared computer model (Adiri, 1969). The model will consist of NT terminals, one CPU with round robin scheduling (a single queue with first come first serve discipline), iid think times that have an exponential distribution with a mean of $1/\lambda_1$, service time requests that are iid with an exponential distirbution with a mean of $1/\lambda_2$, a maximum service quantum of length q (not including overhead), a fixed overhead of length τ for every time slice independent of the length of the quantum. This model is given in Figure 1. Let the objective of the simulation study be to determine the point and interval estimates of the mean steady state response time, where response time, RT, is defined as the time from when a job leaves the terminal until it returns (the time between think times). The expected response time for this model can be calculated as in Adiri, 1969. The model was programmed in SIMSCRIPT II.5 and run on an IBM computer.

4.1 Initial Conditions and Transient Responses

In order to simulate this time-shared computer model, a set of initial conditions must be selected. When one is interested in steady state behavior, it is desirable to select the initial state as a typical state in steady state to reduce the length of the transient response (Conway, 1963). We are going to select for

this case study an initial state that generates regenerative points. This state may not be a typical state in steady state (it may not be for a heavy load on the model). The initial state or conditions selected is when a job leaves the computer and it goes idle. This means all jobs are in the think state. This state generates regenerative points because think times are exponential and the exponential distribution has the forgetfulness (Markov) property.

As stated in the previous section, there does not exist any quantitative procedure to determine when a model's transient response ends and the steady state response begins. Most simulation users simply make an "educated guess" considering such factors as (1) analysis of some realizations (replications) of interest, (2) cost of obtaining observations, (3) concern for transient effect, (4) variability of the model's behavior, and (5) congestion in the model.

This author likes to make three replications and plot the accumulative moving average of the output of interest and use these in conjunction with the factors given above in making his "educated guess" when the steady state response begins. Typically the output will either overshoot the mean value and have a damped oscillation or simply converge on the steady state value. Both of these types of response will have random fluctuations in them. The purpose of using three runs is to be able to evaluate the randomness of the output between runs and to determine what fluctuations mean in a given run. One must remember in analyzing the outputs that you are observing an <u>accumulative</u> moving average. Two difficulties in making these runs are (i) what length should they be, and (ii) what interval should the accumulative moving average be printed out. The run length can always be continued if appropriate information is kept on the state of the model at the end of a run to be used as the input for continuing a simulation run. The interval chosen has to be large enough such that some of the randomness in the output is smooth, yet frequently enough to observe the mean behavior.

Figure 2 contains two sets of three runs of the time sharing model, one under medium load (NT=25) and the other under a heavy load (NT=35). These runs are longer than necessary to illustrate the behavior of realizations of a simulation model. The accumulative moving average was printed out every 20 observations. Two different streams of random numbers are used in each run, one for the think times and the other for service times. The same streams are used in the model for the transient response labeled with the same number. For NT equal to 35, one can readily see that heavy congestion (heavy load) in a model causes more variability and a longer transient response than lower congestion. Some of these realizations illustrate how a transient response overshoots the mean and damps out and others illustrate converging to the mean. This author would consider the transient response ended between 200 and 300 observations for NT equal to 25 and between 600 and 700 observations for NT equal to 35.

4.2 Steady State

Let us determine point and interval estimators of the steady state mean response time of the time-shared computer model with $1/\lambda_1 = 25$, $1/\lambda_2 = 0.8$, $\tau = 0.015$, $q = 0.1$ and NT = 25, with the units being seconds, using the three methods presented in Section 3. This set of parameter values give a steady state mean of 3.415 seconds and is the medium load case discussed under initial conditions and transient responses above. We will use the same initial conditions given above for all our steady state investigations.

For each of the three methods, results will be presented using two replications of the experiment to illustrate the variability that can occur between experiments. For the Batch and Regenerative Methods, the streams of random numbers used to generate realizations (1) and (2) in Figure 2 are used for the experiments (runs) one and two, respectively. The output data from each experiment is analyzed in various ways by varying k, m, N, and the number of observations deleted for the transient response to illustrate how the results can differ depending how the analysis is performed. One must <u>not</u> draw general conclusions from the data presented because of the variability that occurs between experiments, the differences that occur in a model's behavior for different loads, and the differences that occur between different models. The two experiments performed are actually what did happen in performing two experiments (they were not selected from several experiments). One can readily see from Figure 2 that the accumulative moving average of realization (2) never once became equal to or greater than the steady state mean in 1,000 observations. Realization (1) converges very close to the expected value during 1,000 observations.

The distribution of response time in steady state is non-negative, unimodal, and has a long positive tail (Anderson, et al., 1972, 1974), i.e., positive skewness (skewness is a measure of asymmetry of the distribution about the mean and it is positive because the tail is in the positive direction). To illustrate the behavior of the response time distribution a frequency distribution of the data in realization (1) discussed above, is given in Table 1. One can readily see that the distribution has a long positive tail and, therefore, does not have a normal distribution.

Our methods of analysis uses averages of observations and it is the distribution of these averages that must be normal to obtain an exact or approximate sampling distribution. If the observations used to calculate the averages are normal, then the averages will be normal. If the observations are not normal, the distribution of the averages will approach a normal as the number of observations in the averages increase. (Note that the well known central limit theorem cannot be applied directly because our observations are correlated, however, the averages still approach a normal distribution but at a slower rate.) Table 1 contains frequency distributions for 25, 50 and 100 observations in the averages for realization (1). One observes that as the number of observations in the averages (block size) increases, the distribution approaches a normal. An estimate of the coefficient of skewness for each of the three distributions are included in Table 1. This quantifies the effect of increasing m.

If observations of response time are collected from the model one after another, the observations will be positively correlated. Table 2 gives estimates of these correlations using the formulas given in Section 2 for realization (1) after removing the first 200 observations. The correlation decreases as the lag increases and one could estimate that the correlation is zero after a lag of fourteen for this set of data. In using this method of batch means, we must select the number of observations in each batch large enough such that the batch means are independent. This is determined by looking at the correlation of the batch

means. If we use a batch size of 20 observations, correlation estimates using realization (1) are given in Table 2. There is some positive correlation for lag one but is zero for larger lags. This indicates we would most likely underestimate the variance of $\bar{x}$ if we used 20 observations in each block. Using 40 observations in a block, we obtain an estimate of the first lag to be 0.011 for realization (1) and, therefore, the blocks are uncorrelated for blocks of size 40. This analysis indicates that the block size should be greater than 20 but does not need to be greater than 40. Further analysis can be done, if desired. Fishman, 1978, gives a different test statistic and a test to be used to determine if the batches are correlated. He recommends doubling the size of the batch until the test is satisfied.

4.3 The Method of Batch Means

Table 3 contains the results of using realizations (1) and (2) for experiments (runs) one and two, respectively, for various values of N, the total number of observations, for k, the number of batches, for m, the size of each batch, and for different number of observations deleted at the beginning of a run (transient observations). The data for N equal to 1,000 are the first 1,000 observations of N equal to 2,000, etc., for each of the runs. The estimates are obtained as explained in Section 3. $\bar{x}$ is the point estimate of the mean response time, s_B^2 is the point estimate of the variance of the batches, and d is the half width of the 90% confidence interval for the mean, when d is calculated using formula (6). The size of each block, m, is determined by subtracting the number of observations deleted (No. Del.) from the beginning of each run from the total number of observations, N, and dividing the difference by the number of batches, k. For example, with N equal to 1,000, k equal to 5, and the number deleted equal to zero, m equals (1,000 - 0)/5 = 200 observations. Note that the estimate of the mean is not affected by the trade-off between m and k for a given set of observations. Those confidence intervals that do not contain the mean is indicated by an * on d.

The results in Table 3 show what is, in general, expected. $\bar{x}$, the estimate of the steady state mean, approaches E(X) = 3.415 as $\underline{N}$ becomes large. Deleting transient observations at the beginning of the run has only a limited effect on $\bar{x}$ because of the values of N being used, and the behavior of the model for the set of model parameters being used. The difference between $\bar{x}$ and s_B^2 in the two runs is considerable, especially for N equal to 1,000, illustrating the variability between experiments. The variance of the batch averages should decrease as the size of m increases for a fixed k and the values of s_B^2 do. The values for d for different values of k, m, etc. is determined by $t_{1-\gamma/2,k-1}$ times $s_{\bar{x}}$, a function of k and s_B^2. The ratio of $t_{.95,4}$ to $t_{.95,39}$ is 1.265 and, therefore, the value of t does not have a significant effect. The major effect is what happens to $\sigma_{\bar{x}}^2$ for a fixed N in the trade-off between k and m. This effect is problem dependent. The results in Table 3 show that for N equal to 1,000 and 2,000, d increases as k decreases and for N equal to 4,000, d remains about the same. As N increases, d decreases for a given k, as expected.

These results do not determine how accurate the coverage is, i.e., does the 90% confidence interval obtained from the t-distribution actually contain 90% of the actual sampling distribution. One notes that three of the confidence intervals do not contain the mean and this occurs for experiment two when N equals 1,000. This occurs because $\bar{x}$ is a low estimate of μ and the confidence interval is not large enough to contain the mean. For N equal to 4,000, d is less than 10% of μ, the steady state mean.

4.4 The Regenerative Method

Table 4 contains the results of analyzing realizations (1) and (2) by the regenerative method using the classical estimators for various numbers of cycles. The number of observations is also given in Table 4 to enable a comparison between the regenerative method and the batch and replication methods of analysis whose results are given by the number of observations.

In analyzing the data in Table 4, one observes that r_c converges to the steady state mean and d_c becomes smaller as the number of cycles and observations increases, as is to be expected. The coverage of the confidence intervals cannot be determined from the data presented. A 90% confidence interval was used. In experiment two, six of the confidence intervals do not contain the mean, including one having 226 cycles with 975 observations. In analyzing these two realizations (data not presented), most cycles have a small number of observations and the remainder a large number of observations. This means that there is a large variability and these two experiments illustrate that. One notes that the size of the d's are approximately 10% of μ for 450 cycles.

4.5 The Method of Replication

Table 5 contains the results of two experiments using the method of replications for analysis. For each of the two experiments performed, forty runs were made. In the analysis of k equal to forty (forty runs), twenty of these runs were used in the analysis of k equal to twenty, etc. The length of the various runs were such to satisfy the total experiment. When N is fixed and for a given k, the size of m, the number of observations used to determine each R_i, is found by dividing N by k and subtracting the number of transient observations deleted (No. Del.). For example, if N is equal to 1,000, k equal to 5, and No. Del. equal to 50, then m is equal to (1,000/5) - 50 = 150. When N is not given in the table, m is and, therefore, N can be calculated using the definitions given. Note that m is different for the two experiments when N is not specified. A 90% confidence interval has been used.

Analyzing the results in Table 5, one readily draws the conclusion that $\bar{x}$ is extremely variable. Note that a different $\bar{x}$ must be calculated for every case here. When deletion occurs for the transient responses, far less observations are available for analysis when N is fixed, and this increases the variability of $\bar{x}$. When N and the number of observations deleted are fixed, s_B^2 decreases as k decreases (m increasing) and this is as expected. It is difficult to draw any conclusions about the d's except that the more observations included in the analysis, the smaller the d's become. In experiment one, several of the confidence intervals do not contain the steady state mean. This occurs because $\bar{x}$ is very low and d is not large enough to include the value of the mean. Again, we cannot comment upon the coverage unless numerous experiments are performed. The sizes of the d's are much larger in Table 5 for a fixed N than they are for either the regenerative method or the method of batch means.

5. SEQUENTIAL PROCEDURES AND TIME SERIES ANALYSIS

The length of confidence intervals is a function of the number of observations collected and analyzed, the variability of the random variable being investigated, and the probability that the confidence interval contains the parameter being estimated. The three methods of analysis presented in Section III required the analyst to specify the sample size prior to conducting the experiment and are referred to as fixed sample size procedures. In fixed sample size procedures, the length of the confidence interval is not under direct control of the analyst because it is determined by the number of observations fixed prior to running the experiment.

In many studies, one desires to fix the length (width) of the confidence intervals instead of the sample size. There are a set of procedures to allow this and they are called sequential procedures. These type of procedures use a "stopping rule" to determine when sufficient observations have been collected during an experiment to satisfy the length of the confidence interval desired. There are two types of stopping rules: aboslute width and relative width. In absolute width stopping rules, the analyst specifies a constant (numerical value) that is the maximum width (length) of the confidence interval desired. In relative width stopping rules, the analyst specifies the maximum width of the confidence interval desired as some function of the parameter being estimated, e.g., 10% of the value of the estimate of the parameter being estimated. Various sequential procedures have been suggested and recommended for use in performing steady state analysis in simulation (Fishman, 1977, 1978, Lavenburg, et al., 1977, Law et al., 1978, and Pritsker, et al., 1979). Law et al., 1978, have made a limited comparison of several of the sequential procedures and concludes that two of them are better than the other methods they tested.

As an alternative to obtaining independent observations to perform steady state analysis of simulation output data, time series techniques can be used. Simulation output data that is correlated and in steady state is a realization of a wide sense stationary process. There are several time series techniques that can be used to analyze data that come from wide sense stationary processes. These techniques analyze the data either in the time domain or the frequency domain. Techniques that use autocorrelation, autoregressive, and autoregressive-integrated moving averages are examples of time domain techniques. Spectral analysis is the major technique used in the frequency domain. A large number of observations (one long run), knowledge of advance statistics, and in depth knowledge in the time series analysis technique to be used are required to properly apply time series analysis techniques because they are sensitive to proper application. Two advantages of using time series analysis instead of classical statistical analysis are the correlation structure of the data is utilized in time series analysis and the simulation user is not forced to obtain independent observations.

The point estimator of the steady state mean using the time series analysis is still given by (1), but estimates of the variances can be obtained in a variety of ways for each of the various techniques. One method of estimation for the autocorrelation technique is given in Section II. This method of estimation is not considered a good method by several investigators because the $\rho(k)$'s are correlated, the correlation estimator given has a large variance, and some empirical evidence indicate that they are bias on the low side (Duket, et al., 1978 and Law, 1977). Discussion of various time domain techniques are found in Andrews, R. W., 1978, Box, et al., 1970, Devor, et al., 1972, Fishman, 1967, 1973, 1978, Kleijnen, 1974, 1975, and Law, 1979b.

Spectral analysis converts data from the time domain into the frequency domain using sine and cosine waves of different frequencies and amplitudes. The same information is contained in the data but different insights into the behavior of the data can be obtained by using spectral analysis as well as point and interval estimates. Data for spectral analysis is taken at fixed intervals of time. There are numerous ways to obtain estimates of the parameters in spectral analysis and they must be used with care. There has been mixed reaction in using spectral analysis for analyzing simulation output data (Duket, et al., 1978, Fishman, 1967, 1973, 1978, Hunt, 1970, Jenkins, et al., 1968, and Law, 1979b).

6. SELECTION AND COMPARISON OF METHODS FOR STEADY STATE ANALYSIS

When a simulation analyst desires to obtain point and interval estimates of the steady state mean, one specific method of analysis must be selected. The method selected will usually depend upon the specific problem and on the analyst's knowledge of analysis techniques. This author recommends that analysts choose one of the simpler methods of analysis unless they have knowledge in advanced statistics. Thus, most simulation analysts will select a fixed or sequential method requiring independent and identically distributed observations instead of a time series method. Unfortunately, only limited quantitative knowledge is available to aid in this decision.

This author recommends simulation analysts to use either the regenerative method with jackknife estimators or the method of batch means with a small number of batches, say four or five, for obtaining point and interval estimates of the steady state method. In general, the regenerative method should be given preference because it is based upon sound statistical theory and there is no transient response to be concerned with. Unfortunately, in many, if not most, simulations, the regenerative method cannot be applied because the simulation model does not have any regenerative points (or the analyst cannot identify any) or the length of the cycles (time between regenerative points) are so large that the computer costs are prohibitive in obtaining data on the large number of cycles required. (Recall that the central limit theorem is used in developing the regenerative method which requires a large number of iid observations.)

If the regenerative method cannot be used, then the method of batch means should be used. The method of batch means is preferred over the method of replications because (i) there is only one transient response to be truncated and thus the analyst can be conservative and eliminate sufficient observations to avoid a bias point estimator and (ii) this approach has given good results in most empirical studies performed (Law, 1977) using a small number of batches with a reasonable number of observations in each batch. (One may think of the batches in the method of batch means as an approximation to what is being accomplished in the regenerative method in obtaining exact iid observations using cycles.) The number of observations in each batch should be sufficiently large to eliminate correlation between batches and to have the batch means approach normality even when the observations may be far from normal.

In using the regenerative method or the method of batch means, the analyst can choose to use the fixed sample size methods described in Section 3 or choose a sequential procedure. Law, et al., 1978, recommends Fishman sequential method (1977, 1978) to be used with the regenerative approach and the sequential method of Law, et al., 1979d, to be used with the method of batch means. Law, et al., 1978, recommendations were based upon a limited study they made comparing several of the sequential procedures. A note of caution in using the fixed size methods is to make sure a sufficiently large number of cycles are used in regenerative method and sufficiently large number of observations are used in each batch of the method of batch means to enable an accurate confidence interval to be obtained.

7. ANALYZING TERMINATING SIMULATIONS

In the introduction we defined terminating simulations and stated we would delay discussing how to obtain point and interval estimates of means of interest in terminating simulations until we had completed discussing steady state analysis. The reason for this was that the simple method used in terminating simulation is one of the simple methods used in steady state analysis. The simple method used to obtain point and interval estimates of means in terminating simulations is the method of replication. Recall that in terminating simulation, the results are a function of the initial conditions and the time period of interest. Thus in performing the method of replication, the same initial conditions are used in each replication but with a different seed in each of the random number generators to obtain a different realization for each replication. Each replication gives one iid observation to be used in the statistics discussed in Section 2 and 3 for obtaining the point and interval estimates.

The observations of most variables of interest will not be normally distributed and thus a large number of replications will be required in order to use the central limit theorem to obtain normality. This can be quite costly in computer time but there is currently no other method to develop confidence intervals (interval estimates) in terminating simulations.

This method of replication is a fixed sample size procedure if the number of replications are specified prior to running the experiment. There are sequential procedures of both fixed and relative length that can be used in terminating simulations (Law, et al., 1979a). In these procedures, replications continue until the appropriate confidence interval size is obtained.

8. CONCLUSIONS

This paper described in detail the simpler methods of obtaining point and interval estimates of means in terminating and steady state simulations and briefly discussed the other methods. It was recommended that the regenerative method be the first choice and the method of batch means be the second choice in performing analysis of steady state simulations. In terminating simulations, the only simple procedure is the method of replications. In almost all studies performed to date to determine how accurate are the confidence intervals for estimating means in simulations, the size (length) of them were too small. Therefore, a simulation anayst as well as the decision maker using statistical estimates from simulation studies should be cautious in how accurate are simulation results.

A case study was included to illustrate the three simple methods described in detail. The results of this study showed the variability in obtaining estimates from simulations. One should not draw any conclusion from this case study to be used in other simulation investigations. In fact, many simulations will have considerably more variability than this simulation model.

Variance reduction techniques were not discussed, details of sequential procedures and time series analysis techniques were not presented, nor were methods for comparison of alternatives. Methods to determine the sample size in the fixed sample size procedures were not discussed. To obtain sample sizes, one must perform a simulation experiment to obtain point estimates of μ and σ_x^2, then use these estimates to determine the sample size desired. See Pritsker, et al., 1979, for details.

One must always remember that statistical analysis of the output data is only one step in the simulation methodology. The results of the output analysis can be no better than the accuracy of the input data and the validity of the model. Research is continuing into statistical analysis of simulation output data and the simulation analyst should follow these developments.

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TABLE 1. FREQUENCY DISTRIBUTION

Interval	No. of x_i	Interval	m=25 x_i	m=50 x_i	m=100 x_i
0,1	653	0,0.5			
1,2	373	0.5,1.0			
2,3	261	1.0,1.5	8	1	
3,4	181	1.5,2.0	12	5	1
4,5	112	2.0,2.5	12	4	3
5,6	92	2.5,3.0	9	7	4
6,7	67	3.0,3.5	9	8	4
7,8	59	3.5,4.0	7	3	4
8,9	35	4.0,4.5	5	5	3
9,10	37	4.5,5.0	4	3	0
10,11	23	5.0,5.5	4	1	1
11,12	22	5.5,6.0	3	1	0
12,13	18	6.0,6.5	3	0	
13,14	13	6.5,7.0	2	1	
14,15	12	7.0,7.5	0	0	
15,∞	42	7.5,∞	2	1	
Total No. of Obs.	2,000		80	40	20
α_3, Coef. of Skewness*			1.197	1.005	0.582

$^*\alpha_3 = E(x-\mu)^3/\sigma^3$ (normal: $\alpha_3 = 0$; exponential: $\alpha_3 = 2$)

TABLE 2. CORRELATIONS

Response Times

t	$\hat{\rho}(t)$	t	$\hat{\rho}(t)$	t	$\hat{\rho}(t)$
1	0.395	6	0.184	11	0.128
2	0.333	7	0.246	12	0.095
3	0.233	8	0.196	13	0.085
4	0.243	9	0.166	14	0.063
5	0.200	10	0.115	15	0.039

Average of 20 Response Times

t	1	2	3
$\hat{\rho}(t)$	0.164	-0.059	0.034

TABLE 3. BATCH METHOD DATA

N	No. Del.	k / Exp.	5 (1)	5 (2)	10 (1)	10 (2)	20 (1)	20 (2)	40 (1)	40 (2)	$\bar{x}$ (1)	$\bar{x}$ (2)
1000	0	s_B^2	1.026	0.319	1.575	0.517	2.421	1.150	3.785	1.791	3.597	2.943
		d	0.966	0.538	0.727	0.417*	0.602	0.414*	0.518	0.357*		
	200	s_B^2	0.167	0.214	1.086	0.631	3.385	1.489	4.656	2.881	3.679	2.977
		d	0.390	0.441	0.604	0.460	0.711	0.472	0.575	0.452		
2000	0	s_B^2	0.333	0.343	0.752	0.441	1.409	0.943	2.080	1.677	3.298	3.344
		d	0.550	0.559	0.503	0.385	0.459	0.375	0.384	0.345		
	200	s_B^2	0.307	0.376	0.486	0.391	0.929	1.028	2.093	2.430	3.301	3.404
		d	0.529	0.585	0.404	0.362	0.373	0.392	0.385	0.415		
4000	0	s_B^2	0.083		0.209		0.471		1.017		3.377	
		d	0.274		0.265		0.265		0.269			

* Confidence Interval does not contain the mean, 3.415.

TABLE 4. REGENERATIVE METHOD DATA

Experiment 1				Experiment 2			
No. of Cycles	No. of Obs.	r_c	d_c	No. of Cycles	No. of Obs.	r_c	d_c
5	72	4.883	1.588	5	10	0.985	0.448*
10	78	4.546	1.588	10	19	0.851	0.302*
20	128	3.582	1.469	20	39	1.120	0.521*
40	173	3.148	1.228	40	131	2.896	0.851
80	336	3.464	0.876	80	363	1.905	0.747
160	780	3.681	0.648	160	728	2.938	0.469*
164	784	3.669	0.647	191	793	2.817	0.430*
219	988	3.604	0.561	226	975	2.887	0.386*
320	1451	3.496	0.453	320	1431	3.126	0.351
361	1584	3.378	0.433	351	1598	3.208	0.365
402	1796	3.355	0.395	396	1800	3.264	0.353
450	1988	3.301	0.367	418	1987	3.333	0.341

* Confidence Interval does not contain the mean, 3.415.

TABLE 5. REPLICATION METHOD DATA

N	No. Del.	k	5		10		20		40	
		Exp.	1	2	1	2	1	2	1	2
1000	0	$\bar{x}$	2.634	3.423	2.857	3.597	2.944	2.975	2.646	2.606
		s^2	0.237	0.595	0.437	2.785	1.161	3.276	1.994	2.066
		d_R	0.464*	0.736	0.383*	0.968	0.490*	0.700	0.375*	0.383*
	50	$\bar{x}$	2.672	3.659	2.962	3.939				
		s^2	0.127	0.641	1.371	1.825				
		d_R	0.340*	0.764	0.679	0.783				
2000	0	$\bar{x}$	3.228	3.493	2.798	3.538	2.934	3.352	2.881	3.068
		s^2	0.355	0.237	0.334	0.825	0.474	2.346	1.637	2.150
		d_R	0.568	0.465	0.334*	0.526	0.266*	0.592	0.341*	0.391
	50	$\bar{x}$	3.330	3.605	2.813	3.633	3.125	3.728		
		s^2	0.317	0.284	0.194	0.445	1.482	2.160		
		d_R	0.537	0.509	0.255*	0.287	0.471	0.568		
	100	$\bar{x}$	3.408	3.555	2.738	3.480				
		s^2	0.524	0.323	0.956	0.596				
		d_R	0.690	0.542	0.567*	0.448				
	200	$\bar{x}$	3.823	3.564						
		s^2	1.141	0.406						
		d_R	1.019	0.608						
	200	m	160	360	80	180	40	90		
		x	3.674	3.442	3.690	3.284	2.782	3.686		
		s^2	1.341	0.060	1.702	0.432	1.115	1.274		
		d_R	1.104	0.233	0.756	0.381	0.408*	0.436		

* Confidence Interval does not contain the mean, 3.415.

FIGURE 1

TIME-SHARED COMPUTER MODEL

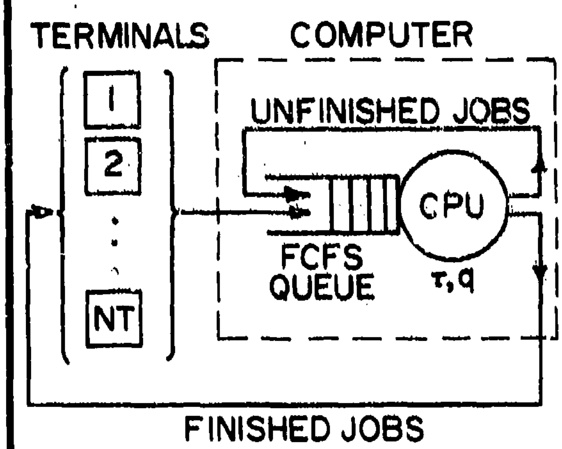
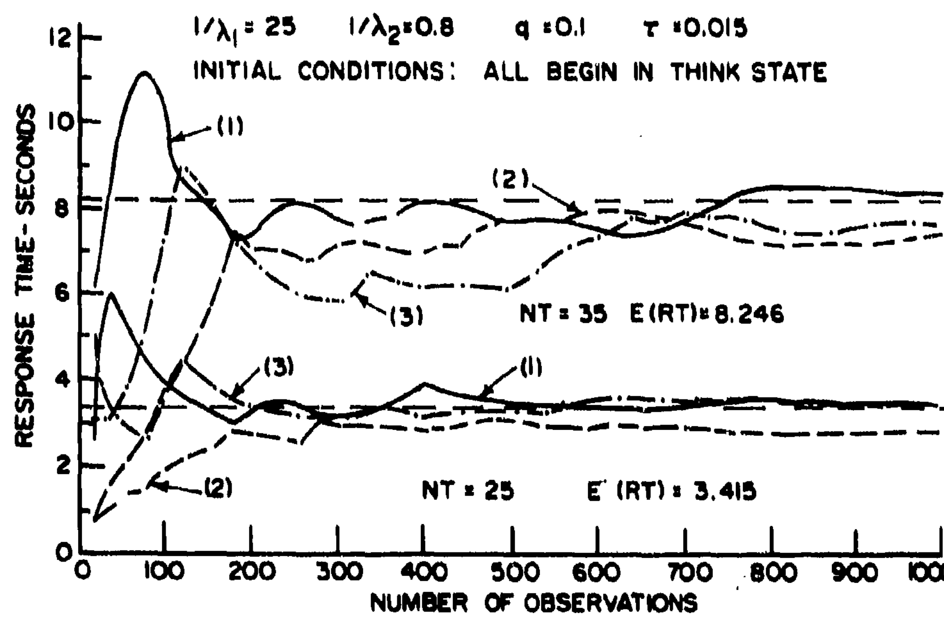


FIGURE 2 TRANSIENT RESPONSES



Remarks on Simulation

objectives/areas of use/possibilities/limitations

- an overview -

Hans M. Franke
Dipl.-Ing; Prokurist
Director: Military Technology Studies (WT)
Industrieanlagen-Betriebsgesellschaft mbH
Ottobrunn, Germany

SUMMARY

A definition of "What is Simulation" is followed by some classic experiences and knowledges. Simulation is widely used in Systems Analysis to understand problems in planning of new weapon systems. Here simulation - another tool beside calculation and experimentation - serves for operational as well as for technical investigations. In the field of Systems Technique by the activities of "systems engineering"

- o alternative, parametric, conceptual predesigns are generated
- o the technical feasibility must be investigated
- o the integration of sub-systems to a total system must be studied
- o the relations between technical performances and reliability and maintenance must be taken into account
- o the efficiency of technical performances must be set into relation of funding for R & D, procurement and for operation.

The systems engineer - responsible for the predesign - has here to handle with assumptions about 15 to 25 years in beforehand and the systems engineer's tool for studying the dynamic behaviour of a system is called "simulation".

Within the scope of this essay, objectives, areas of use, possibilities, limitations in the field of simulation are mentioned.

Final remarks are aimed on important, evolutionary branches in avionics and C^3 and on technology transfer.

The paper concludes on the importance of intensive use of simulation.

1. INTRODUCTION

1.1. Definition of Simulation

This essay should start with a classic definition on the activities and areas of "Simulation". For this the statement of Brockhaus Enzyklopädie [1] is used because the author has made the experience, to get a well accepable description in every situation. (See Fig. 1). For digging a little bit deeper, it has been tried very often, to create families of standards like "hard-ware-simulation" or "soft-ware-simulation" - however with rather little success. In practice different applications have been adopted, but is has been proven right, that simulation is characterized at all times by

- o obtaining the results of investigation by using a model
- o considering the timely passing of the events.

In so far the simulation is differentiated essentially from the calculation on one side and the experiment on the other. Frequently simulation and test occur in combination of course; for example at fatigue-testing of an aircraft structure - the real structure and not a model is used as specimen - the airloads are simulated.

For this AVP meeting, dedicated to C^3, it should be amusing to point at mixed types of simulations in the light of the famous example from biology, where it could be clarified, that the honey-bees navigate by means of radiation of the sun

case 1	bee real	sun real
case 2	bee real	sun simulated
case 3	bee simulated	sun real
case 4	bee simulated	sun simulated

According the circumstances — scientists, engineers, can point their interest at the "inner loop" or the "outer loop" of signal flow in a system — types of simulation like cases 2, 3, or 4 can be applied.

1.2. Retrospective View

The push of innovation in the field of electronics has entered in wide areas of our life — perhaps in predominant cases; perceived by the human beings or not —. Relative to the possibility/feasibility, performing a simulation, some experiences made by the author should be reported on. At the end of the fifties / the beginning of the sixties the extensive application of simulation began for investigating flight mechanics f.e. flying qualities, handling qualities of vertical-take-off-and-landing-vehicles (VTOL-aircraft). [2]

The reproduction/the ability of transference of flight experiences with helicopters has been doubted and on the other side it has been assumed too dangerous to start with free flying tests and after all pure calculations let not discover the total dynamic behaviour of the vehicle plus its control system.

The analog computer technique - at that time the training simulators of civil transport aircraft as well as military fighter aircraft based on the analog computer - has been used, to lay out / to design the control- and steering-system for airplanes and to investigate flying qualities and to formulate pertinent criteria. Large analog computer centres have been established, but as well the investment in machinery as also theoretical questions / influences of accuracy and ability of reproduction did no longer allow, to investigate systems which became more and more complex, economically and technically correct.

That was the moment, digital computers have been used for the first time for flight simulations. Nevertheless there has been no chance to fly a simulator in real time. Scientists and engineers came together in meetings, to discuss possibilities and constraints in the application of the digital computer and to estimate the trend into the future. As an example for such a meeting, the "Congres de l'Aeronautique sur le Technique de calcul analogique et numerique en aeronautique" at Lüttich in the year 1963 should be mentioned. [3]

The author worked in those years 1961/62 on the dynamic behaviour of components in a VTOL aircraft flight control system (f.e. hydraulic cylinder with limited max. speed and with deflection limitation). He has written the program for digital simulation and a digital computer IBM 650 has been used for an investigation of the handling qualities of a flying, hovering bedstead.
All components of the controlsystem have been modelled, meanwhile the vehicle has been described only by mass and inertial moments (no aerodynamics). To receive a result on approximate 3 minutes of flying time the computer (at those days) had to run for about 5 hours; the cycle time — to integrate through all the differential equations — was low and furthermore one had to reserve on the computer's memory size (over lay).

In Fig. 2 some typical characteristics on digital computers of that era in comparison to the modern one are shown. This may point at the limitations in those former days, which made some racking of the engineer's brain — and this may point at the matter of fact, that at present there exist possibilities, at which no engineer formerly ventured to dream.

The break-through — application of the digital computer with high computation / cycle speed and large memory size — happened by the successful

- o increase of the performance in transistor function per chip and that together with the price-reduction
- o treatment of numerical mathematics
  - non-linearities
  - systems for differential equations.

The well-known trend in hard-ware technology is shown in Fig. 3
It should not be forgotten, that this increase in over all performance is also characterized by the improvement of the system's soft-ware. In total the number of instructions could be increased from 10^4 in the year 1958 to 10^7 in the year 1978 [4].

Now some limitations in the further improvement of the hardware performances will be indicated, [5]

tact time per transistor function:	year 1948	Mikrosecond
	year 1968	Nanosecond
	year 1988	Pikosecond

but from a simulator specialist's point of view it can be stated, that the hardware has achieved an acceptable niveau with good reputation, meanwhile emphasis must be pointed at the software. From a simulator specialist's point of view, the hardware of today fulfill the requirements for the basic requirements on accuracy and memory size adequately, although other specifications like wheight, volume, power, reliability can be / must be / will be improved.

These steps in these two decades showed to us:

- o to differentiate the situation of a user of a centralized commercial computer-facility (closed shop) from that of a design engineer developing hardware and software f.e. in avionics and C^3 using simulation
- o no longer to rely on a given type of a computer
- o but to understand the computer as a system assembled from hardware and software.
- o in so far not to try to increase the computer performances by improving only the hardware efficiency

and other things more.

About 10 years ago it has been intended to simulate the improved functions of a future computer by use of an existing computer - this is past. In the same way it is past to centralize all the required computation power as necessary in a complex technical system like an aircraft into a central computer. At present we can see turning away from the total integration. Recently for the design of a most modern aircraft flight control system emphasis is layed at the decentralization of functions (primarily on account of economic advantage)[6]. As well in the military technology field as also in operation with civil air carriers an "optimal structure of the system" (system's architecture) is aspired; that means

- o decentralization of the computing power with respect to the distinct functions in such a way that the computing system structure is adequate for a family of equipment (f.e. a family of jet transport aircraft)
- o consideration of single, specific characteristics pertinent to a particular type within the family, in relation to the functions decentralization.

There are many other stories about history — but only the following remarks should be given:

- o simulation is now used in special branches
- o today a large number of institutions work on fundamentals for simulation techniques and on application of simulation
- o today a large number of meetings occur on the matter of simulation
- o at NATO simulation and simulation results are discussed as well in the AVP Panel as in other Panels and furthermore in many NATO groups (AC...)
- o the number of publications on simulation has been increased rapidly [7] to [18] .

At the end of this retrospective view it can be stated, the digital computer in use for simulation is now an exeptional tool for the engineer / scientist.

1.3. Contemplations on systems in avionics and C^3

This AGARD meeting is pointed at the application of simulation in avionics and command & control and in communication. Fig. 4 shows an example on air-defense implying all the detailed use of avionics and C^3.

This Fig. 4 should be representative for a number of functions, activities, components etc. by listing up (as examples) the following items

- o command & control
- o avionics
- o outer loop
- o inner loop
- o computer: hardware / software
- o data transmission
- o traffic control
- o communication
- o identification
- o a/c flight control systems
- o navigation
- o weapon delivery
- o counter measure
- o others

It is the aim of this meeting, to discuss on simulation applied in the most different branches and under most different situations / questions / aims of investigations.

2. AREAS OF USE OF SIMULATION / SIMULATOR

2.1. Survey

The simulation is used as a scientifically established tool beside the experiment and beside the calculation. This is shown in Fig. 5.

Simulation is applied for

- o technical tasks
- o operational tasks
  (in the case of military questions)
- o other.

The dotted line in the left-hand-side of the figure should express, that simulations and tests frequently go together in combination.

As examples for ecological / economical investigations, the models of Forrester and Meadow and some treatises of other persons are normally mentioned [19] to [21] .

By Fig. 6 it should be expressed that simulation is applied in different activities, following one each other in sequences, called research, planning and assessment, development and testing, training. It must be remarked that different simulation tasks demand for different simulator installations. This depends on the matter of fact, that simulations are always approximations — namely because of technological and economical reasons. Therefore in every case the correlation of simulation to real world must be proved adequately. This is also pertinent to the pure mathematical simulation, which is shown in Fig. 7 in opposite to the simulation with "component in the loop" or extremly "man in the loop". By this, the requirements for a real time simulation and for generating of the environmental cues are pointed at. It is evident, that the highest demands must be engaged in the case of simulation with "man in the loop".

2.2. Simulation in the field of research

Simulation is widely used in the fields of research.

As one example, the simulator installation for investigating fundamentals on "computer generated images" can be mentioned. The aim of such a task is to investigate how much accuracy is required - and in consequence how much money must be spent - for providing acceptable environmental cues to a pilot or in other words where is the lower limit for simplificating of such a technical device just still producing adequate/acceptable cues to the pilot.

Another example is the use of a flight-simulator for investigating handling qualities criteria.

As a third example, in Fig. 8 a movable cabin is shown. It is used in research on environmental cues to a pilot. Particularly interdependencies between acceleration cues and visual cues are investigated. A typical question is, to which degree an acceleration can be supressed or neglected in presence of visual cues or in other words by which degree acceleration cues can be replaced by visiual cues.

2.3. Simulation for planning, pre-design, assessment and feasibility-transparency

In modern weapon systems we can see the increase in technological complexity. This is followed by a high risk in development, by higher cost for development and other consequences. This demands already at the beginning of the planning for new technical future systems the more intensified use of systems-engineering activities. As an example for applying simulation in the early planning phase the "Dual-Flight-Simulator" of IABG, Germany, is shown in Fig. 9. This installation is described in detail in several publications, f.e. in [22]. With respect to the state of art in technology and with respect to the application this instrument is comparable to the "Manned Aircraft Combat Simulator (MACS)" of McDonnel Douglas and to the "Dual maneuvering Simulator" at NASA Langley. See also [23] for a more general explanation.

Already at the "Congres sur le Technique de calcul.." in the year 1963 the author has pointed at the necessity to investigate the dynamic behaviour of a system by the use of simulation already in a pre-design-status that means in a technical feasibility study before the beginning of the real development. In [24], the author explained, that initial results and experiences on the interdependencies and the collective actions of all subsystems (f.e.: basic aircraft, control system with all components, flying quality criteria, feasibility, integrability, efficiency and reliability), simulated on the basis of the first lay-out-design, must be retransferred to the project/design bureau, thus improving the first approximated design.

2.4. Simulation in the development phase

It is normal practice for the engineer, responsible for the development of a new device, to perform designs, constructions and computations. Studying the dynamic behaviour he uses the simulation. Starting with a pure mathematical simulation for specifying the technical requirements on the new component, the mathematical models will be replaced step by step by the real - brand new built - component such realizing the so-called "iron bird". In Fig. 10 the iron bird of the MRCA aircraft - the flight control test rig - is shown.

In the field of the software also simulation is used as a tool for developing and optimizing software. Fig. 11 gives some explanation on the structure of such a type of simulation.

2.5. Simulation during testing

Every technical development is finished by an acceptance test. Also in these cases - certification of required performances and particularly safe operation - simulation is used. It can be said, that in many cases acceptance tests can be performed only in connection with simulation. Typical examples are shown in Fig. 12 (testing the avionic equipment of an aircraft) and in Fig 13 (fatigue testing the main structure of a civil transport jet aircraft).

2.6. The Training Simulator

The training simulator is a well known instrument. Even civilian people / travellers have heard about simulators for civil transport jets used by the captains. As an example in military use Fig. 14 shows the "cockpit operational Fighter Trainer" for the A/C F-4 as in service with the German Airforce. That is a typical device for procedure training. Other types of procedure training simulators are

- o gunnery simulator
- o guided missile controlling simulator
- o battle tank driving simulator
- o submarine controlling simulator.

3. ACTIVITIES PRIOR TO WEAPON SYSTEMS DEVELOPMENT

3.1. Problems

Frequently there arise the questions - perhaps at the end of the development of equipment or during the operation in service - whether the original requirements have been met by the now completed technical system and whether the actual cost corresponds with the planned expenditure. In a reverse case another question asks for the reasons of discrepancies. Those questions are terms of the problems, constraints and influences in the weapon system's acquisition process of modern, future, complex, technical systems like weapon systems. It is the aim of the systems planning process to balance the technological improvement in relation to time (operational availability) for meeting the military / tactical requirements, the risk (primary increase in cost) and the life-cycle-cost. (See also [25]).
In a simplified style, Fig. 15 explains the steps from the frist pre-design to the real end product. At the beginning there will be stated the requirements, leading to the first pre-design. Then the subsystems and components are designed, calculated and constructed separately. Finally these subsystems are integrated and all people — envolved in these development stages — now hope, that the now completed prototype will work as specified at the beginning. Experienced engineers detect immediately, that the simplifying assumption, to treat the subsystems and components as independent from one to each other, can and will lead to the most unpleasant difficulties.

Fig. 15 gives an additional information on the time frame necessary from the formulating the requirements till the completion of a development by qualification test in the case of a modern complex weapon system. In Fig. 16 this life-cycle is shown, demonstrating that today the planning phase endures about 5 years, the development about 10 years meanwhile the operational use in service will cover about 20 years.
Fig. 17 should point at different ways to obtain systems with different total life-cycle-cost, but mentioning

a) the problems of the existence of different budget titles for R & D, development and for operation (problem of follow-on cost)

b) emphasis on more detailed activities in the forefield of the real development, for better estimating the life-cycle-cost in the situation of early planning and for better support on the decision-makers, to interpret the total budgeting in relation to the weapon system's effectiveness.

It seems to be necessary to look at this situation also from another point of view. It is a matter of fact, that higher tactical / operational requirements in accordance with more sophisticated technology - to meet the initial requirements - result in higher development cost and higher single unit prices. Here the question must be discussed, whether a reduction of the number of units procured (perhaps as a consequence of a unforeseen raising of the price) can result in a decrease of the over all defense capability. This would mean, in spite of the improved performances of a weapon system, not to lead automatically to better defense capability. It is the quantity, that influences our efforts.
For better understanding these circumstances, it seems to be favourable, to investigate these situations under all constraints already in the forefield of the development. These experiences lead to the more strictly sequenced process of planning. The situation and interdependencies, the sequences and the instruments solving the task have been described very pregnant already in 1970 by WAHL [26] .

3.2. Systems analysis

For optimal sequencing and better managing the planning of development itself a particular relevant regulation became operational in Germany in 1972. This regulation - called "Entstehungs- und Beschaffungsgang von Wehrmaterial (EBMat)" - orders some particular activities before the beginning of the development. It is directed to the same goal like the "US weapons acquisition process", even if there are some remarkable differences. In the EBMat it is stated, that in the first phase so called "study groups" should define "tactical requirement-papers". These study groups will be supported by operational analyses and by technical feasibility studies. [27]

System analyses are applied to investigate

- o the technical feasibility
- o the operational effectiveness
- o the budgeting possibilities / necessities.

A definition on Systems Analysis is presented in Fig. 20, describing an iterative process starting with a first approximation. For this, a first technical pre-design as an "idea of solution" must be created. In most cases, it is benefitial, to provide for a spectrum of alternative, parametric, conceptual pre-designs of future weapon systems, followed by operational investigations (OR-studies) to filter out those designs, that are out of interest from an operational point of view. The remaining technical design can now be improved and they will be used in the next step of the iterative process. [28]

3.3. System's Engineering Activities

Today all extensive, large technical projects will be accompanied by what is called "systems technique". It is now practice - at least in Germany - to call the first activities in this technical field "systems engineering", this means to produce a first pre-design: (see Fig. 22).

The goal aspired is the conceptual system pre-design. Significant terms are

- o design principles
- o sensitivity
- o compatibility / systems integration.

By the technical design as a connecting link

a) performances can be calculated
   attention to - reliability and vulnerability
   - maintenance / maintainability

b) cost-estimation can be made
   - R & D
   - Procurement (single unit).

Fig. 22 demonstrates the sequences in activities for producing a new weapon system starting with research and finishing with bringing this equipment into operation.

System engineering activities in Germany are performed in the industry firms within the Future Technologie Programs.

Furthermore system engineer studies are treated at the system-engineering groups (WT) at IABG directly for the German MoD. The aim of such studies is defined by:

a) for the Armament Offices:
   - o technical studies for investigating the technical feasibility (plus cost-estimation) during the early planning phase
   - o neutral, critical assessment of proposals from industrial competitions on new weapon systems

b) for OR-activities:
   - o generation of technical data on description on function/ mechanism of weapon systems as input data for operational studies.

The most important problem-areas from the system-engineering point of view are:

- o the forecasting on the progress of scientific / technological basic parameters (see Fig. 23)
- o the realization and the stipulation of the quantity performances, reliability and maintenances, which are exchangable to some amount (see Fig. 24)
- o the integratibility of the components to the total system (compatibility and sensitivity).

To discover - already in the presence - risk-components and problematic technical interdependencies and sensitivities, which could emerge at the production of the frist prototype, the pre-design engineer has to assume the state of the art in technology of about 20 years in beforehand. Such a forecasting is affected with some amount of uncertainty and the problems are wellknown if two trend extrapolations are in contradiction (Fig. 23). Surely such a case indicates a risk situation.

Fig. 24 points at the necessity, that the technical performances must be produced in accordance with adequate reliability and in relation to a well described maintenance concept. Distress make all those components / systems, of which the performance is forced with a debit of reliability (penalty) on the other hand. Also there will be some trouble with systems in the operational phase, if the maintenance concept is not well considered (additional cost for maintenance).

For being effective, for investigating sensitivities [29] of basic scientific-technical parameters within the integrated systems, for understanding the feasibility and for being able to describe dynamics (all this in the early phases of planning a weapon system) there are two remarkable methods in use with the engineer

- o the computerized parametric design [30]
- o the simulator.

These engineering tools have been used highly successful.

3.4. The Future Technology Programs

The Future Technology Programs are the tool / the method / the way for generating know-how for the future.

These programs for and on behalf of the Armament Division of GMoD are well described at other occasions and in particular papers [31] and [32] .

The Future Technology Programs are already mentioned in Fig. 22 (ZT-Programme und KE-Programme), where they are described as beginning in the forefield of the activities of development planning. They give emphasis to critical future components, provide for advanced methods and technology, are aimed to the investigation of the sensitivity of interdependencies of components working together in a system and provide for conceptual predesign.

Fig. 25 gives an overview on the Future Technology Programs of the GMoD. Studies, investigations, experiments and calculations and simulation under the notation "Future Technology Programs" are mainly performed in potential industry firms for and on behalf of the Armament Division of the GMoD.

In particular in Fig. 25 the program for aero-space-technology (ZT-Luft) is described in a little more detail. There are working groups for methods and components and subsystems, while working group 1 is responsible for proposals on pre-designs based on conceptual topics.

3.5. Simulation as a tool of the systems engineer

Within the scope of the Future Technology Program and the systems engineering activities, numerous and extensive simulations of all types are performed in industry firms, research laboratories and other institutions.

For the use on the governmental side, the simulation centre (WTS) at IABG has been established - starting in 1969 - for and on behalf of the German Ministry of Defense [33]. The essential feature of this simulator centre - shown in Fig. 26 - is its flexibility and applicability for technical systems that are in planning for the three single forces army, navy and airforce. The main parts of it are

- o the computer capacity in the middle of the building
- o four experimental fields (at present 2 fields are used for the Dual Flight Simulator)
- o a mechanical workshop
- o an electronics laboratory and manufacturing capability
- o a particular room for anthropotechnical experiments.

It should be mentioned as a matter of fact, that this simulator centre can (by order of the German MoD) work in cooperation with the industry if necessary in extensive projects - and that has been done together with governmental offices / agencies, industry firms and research institutes.

Some remarks on the configuration of the computer capacity could be of interest (see Fig. 27). With respect to the flexibility (efficiency) and adaptability

- o this computation capacity is not coupled to another computer centre
- o a particular system's software is used
- o the concept of interconnecting or splitting the computer capacities is fully applied.

This concept has proved excellent.

3.6. Limitations / Constraints

After so many remarks on the possibilities and the advantages of simulation it is necessary also to point at the limitations accompaning the simulation. Due to economical efficiency it must be aspired to run the most simple simulation. Alone the requirement for good correlation of simulator results to the real world forces us to use a more sophisticated type of simulation. Therefore some emphasis must be laid to find out this optimal type of simulation, which produces adequate results and which is at the same time economical justifiable. The increasing complexity of the weapon systems, that are investigated by simulation, as well the situation, that all the subsystems are in most cases no longer independent from each other (!), demand also more complex, more sophisticated simulations and simulators.
For example highest degree of attention must be directed on the imitation / modelling of the environmental cues, if the simulator is controlled by a human being. That is the task of a large number of scientists and engineers (in technique, ergonomics, physiologics and others) to investigate technical possibilities / devices to achieve these requirements. [34]

4. USE OF SIMULATORS (national facilities)

Simulation is a quite normally used tool at all steps in planning and producing a modern weapon system. It is applied at all institutions involved in this work. Therefore in Fig. 28 the author tried to collect a survey on those institutions and the aim of the simulations. This table is arranged in the different fields of activities. This table demonstrates, that simulation can be seen in use widespread and therefore widespread experiences can be met.

5. IMPORTANT BRANCHES IN AVIONICS AND C^3

On the basis of experience with modern weapon systems and with pre-design-studies of future equipment, some remarks should be made on important branches which are in relation to this AVP meeting or to the Avionic Panel generally.

In Fig. 29 such fields of interests are listed up, which can itself experience an improvement of the technology by the pres of innovation in electronics. It is hoped, that these applications will be transferred from an experimental status into successful use.

It is absolutely sure, that the improvement of the performances in those branches will produce a contribution to the improvement of weapon systems or it will permit to create total new types of weapon systems and / or it will enable for other tactics.

As well it is sure, that the successful carrying ahead of these technologies will occur by extensive use of simulation.

6. ON THE TECHNOLOGY TRANSFER

It must be mentioned, that there is no possibility to describe here all the branches, types and aims for which simulation is applied.

Therefore it must not be listed up here, from which technology branch a know-how transfer can be provided into another.

But from the experiences of the author, the remarks should be derived how much the work in simulation brings together the specialists of different branches. The total field of simulation implies the matter of fact, that different experiences impact one each other, that interdisciplinary kick-off will be generated and that this transferred know-how will spread out in different directions.

Already by this indirect manner - because of discussing how to perform simulation - an exceptional amount on technology and know-how transfer is guaranteed !

7. CONCLUSIONS

Occasionally there is the question asked to which degree simulation is used in a correct way and in sufficient extent (in the steps: research, planning and assessment, development and training).

The experiences from the past and the current activities allow for the following statements (from a national point of view)

a) Simulations will be normally performed in a technological most modern form because the specialists are steadily working on the relevant fundamentals and simulations are normally performed in explicable correlation to the real world, because every well-reputed simulation today is accompanied by the interpretation of the correlative situation.

b) With respect to the budgetary possibilities it can be said, that the different types of simulation in research, planning and assessment, development and training are performed correctly and are used sufficiently.

With some statements in Fig. 30 this essay will be completed.

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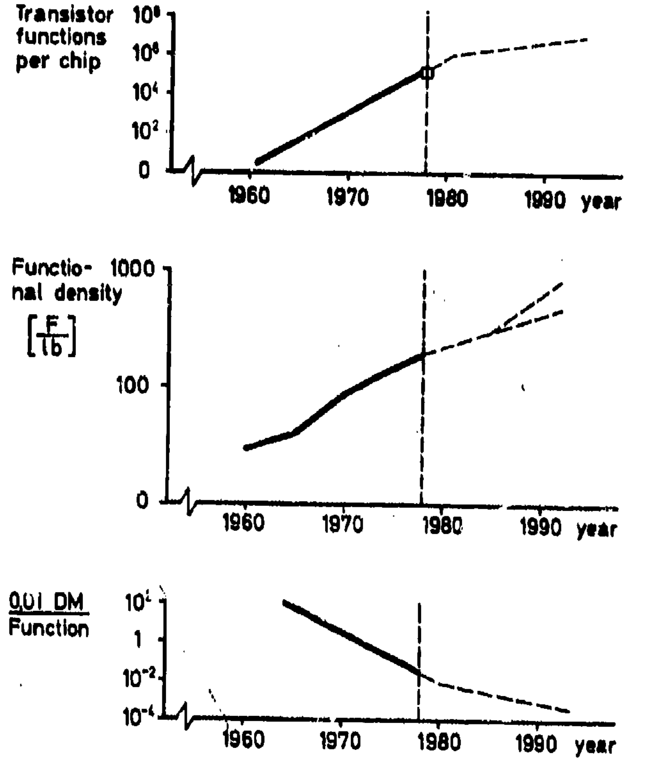
Collective
for description and for imitating
physical, technological, biological, psychological or economical
processes or systems
by mathematical or physical models
whereby the investigation of the model
is easier, cheaper or less dangerous as the original real piece
and
whereby the results admit conclusions on the nature characteristics
of the original real piece

after [1]

Fig.1 Simulation - - a definition

	Year 1960	Year 1979
Type	f. e. IBM 650	(f.e. IBM 370 series) f.e. IBM 4341
operations per sec:	$< 10^2$	$\sim 10^6$
memory size:	$\sim 5 \cdot 10^3$	$\sim 4 \cdot 10^6$ ($\triangleq$ 4 194 304 byte)
spezif. price for 10^3 ops/sec:	~800 000 DM	~ 600 DM
languages:	FØRTRAN IV	o High Order Language o CSSC o Advanced continuous simulation language (ACSL)

Fig.2 Historical comparison (some characteristics)



after [4] and [5]

Fig.3 Trend "integration technology"

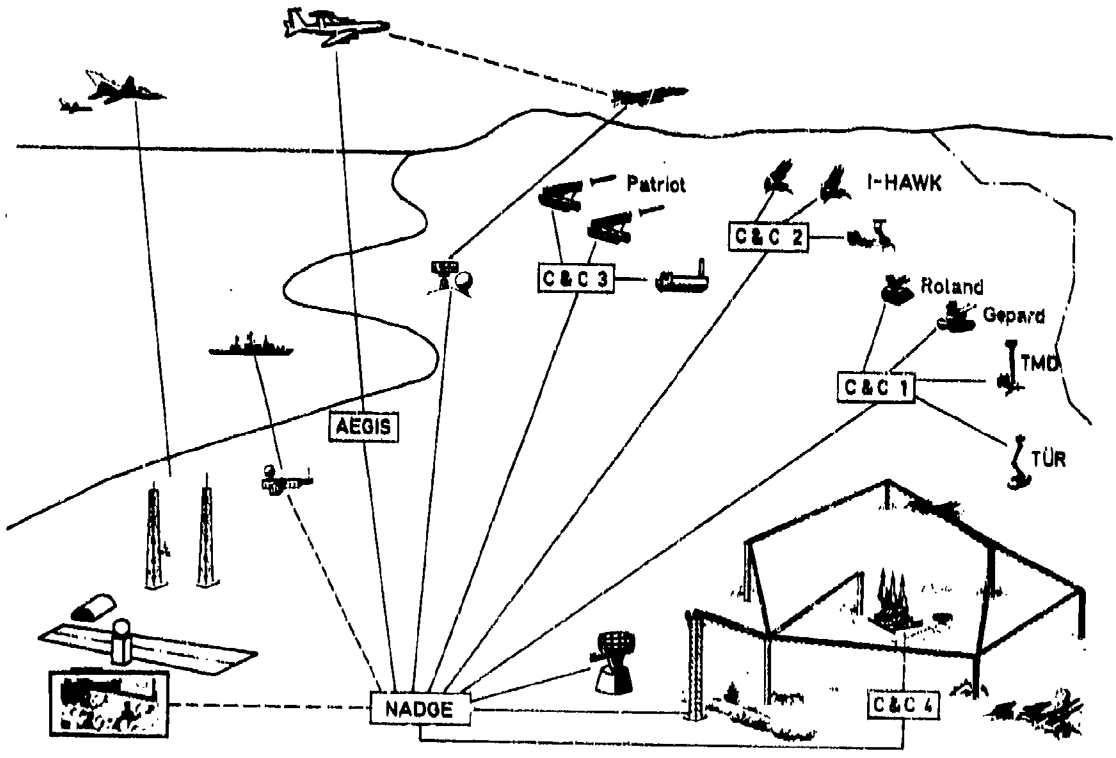


Fig.4 Avionics and C³ (example: air-defence)

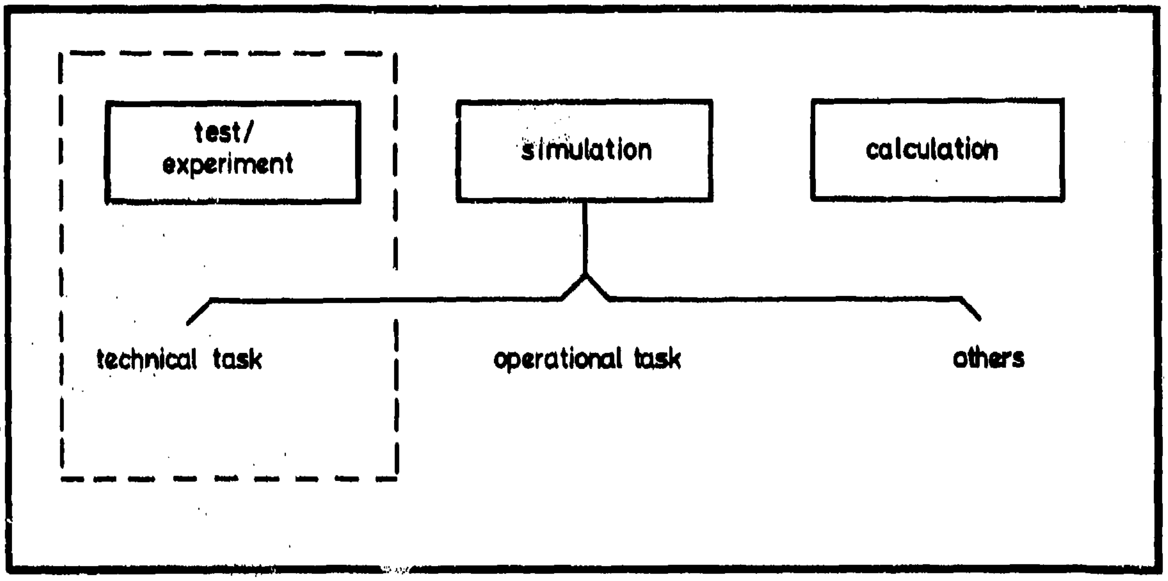


Fig.5 Simulation – another method beside "test" and "calculation"

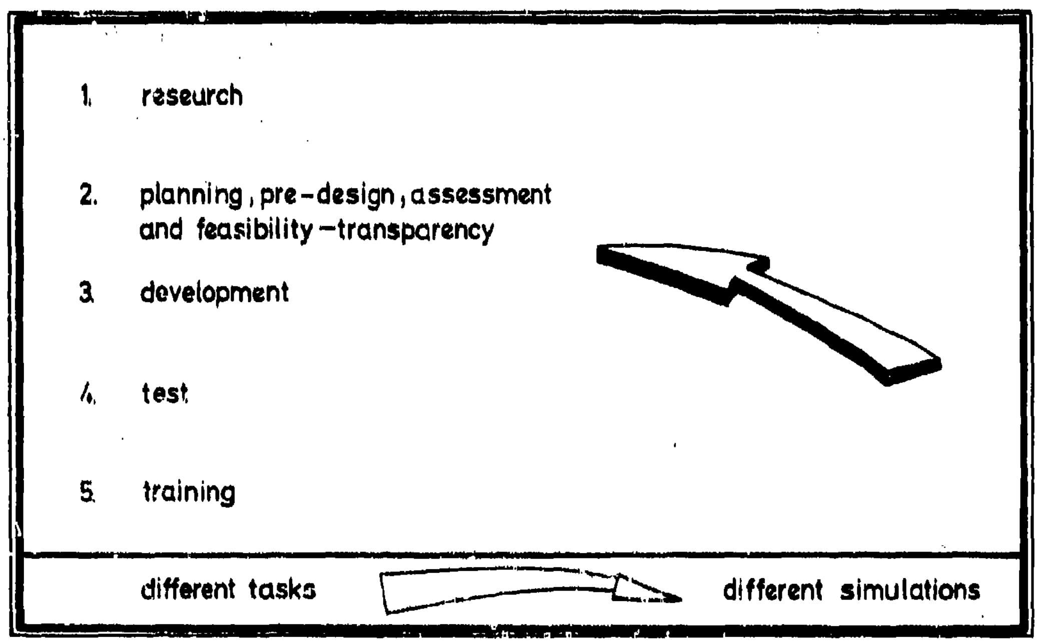


Fig.6 Simulations/simulators – fields of application

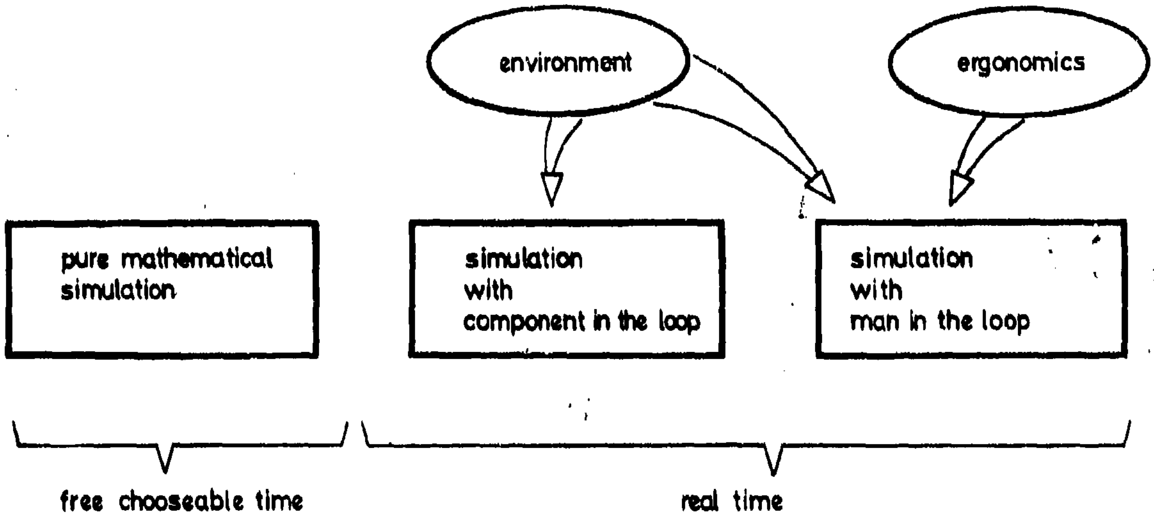
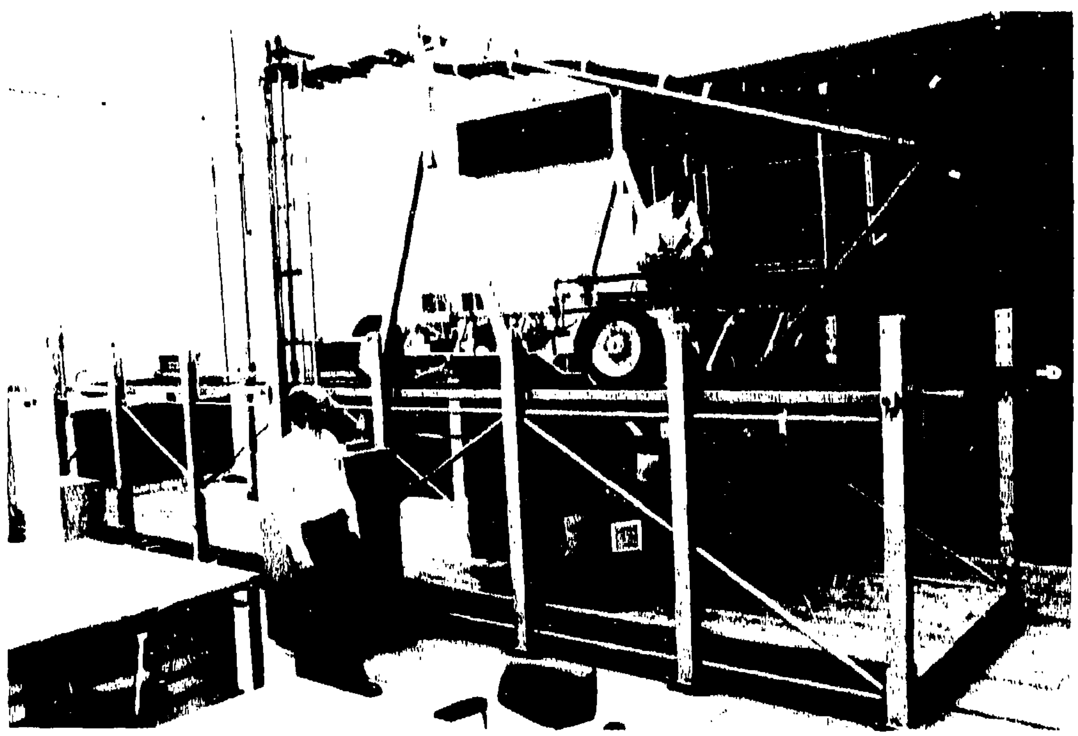


Fig.7 Simulation -- a sort of classification



by courtesy of FGAN

Fig.8 Simulation in the field of research

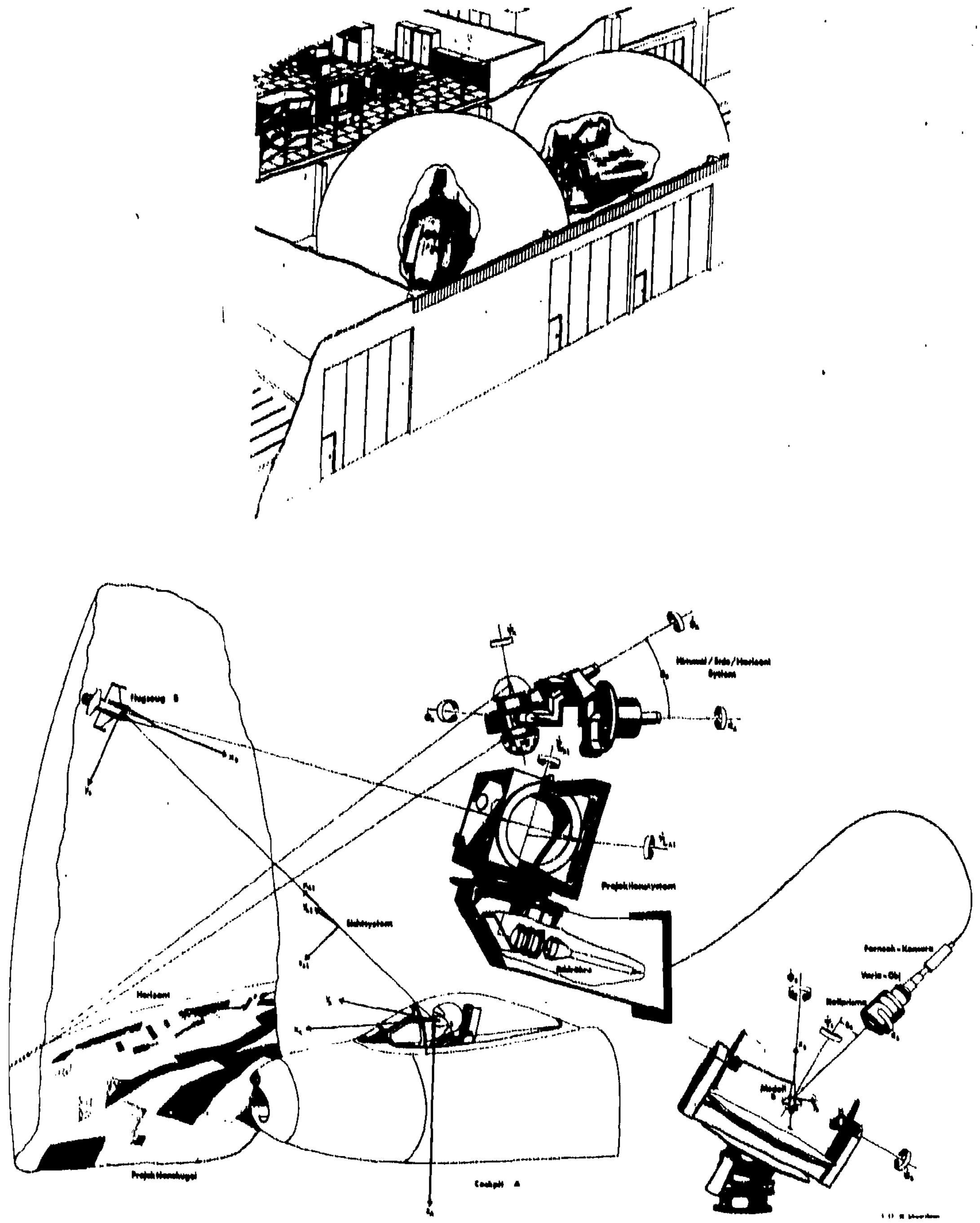
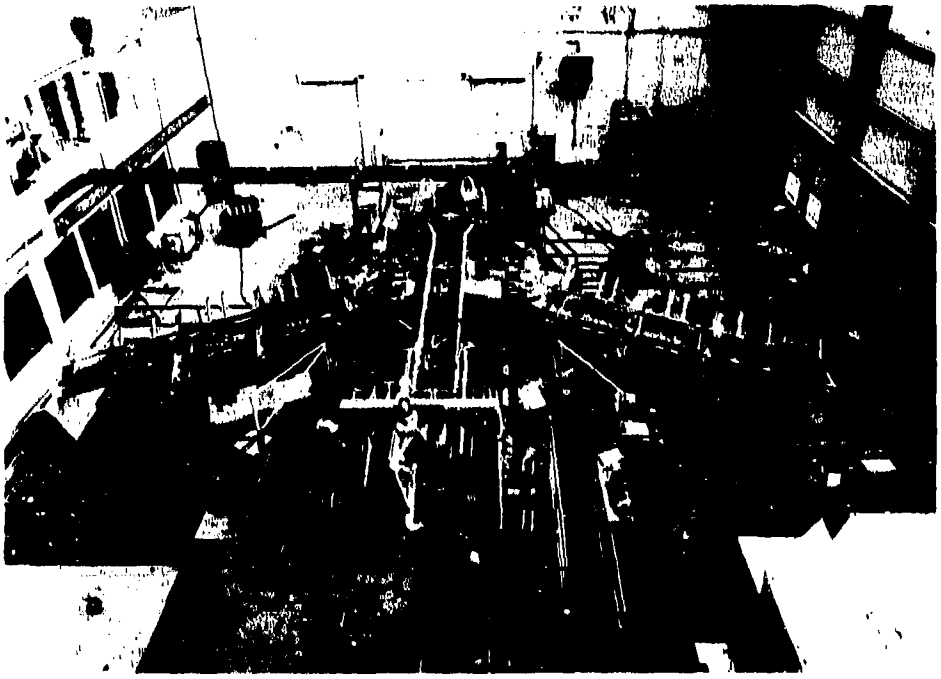
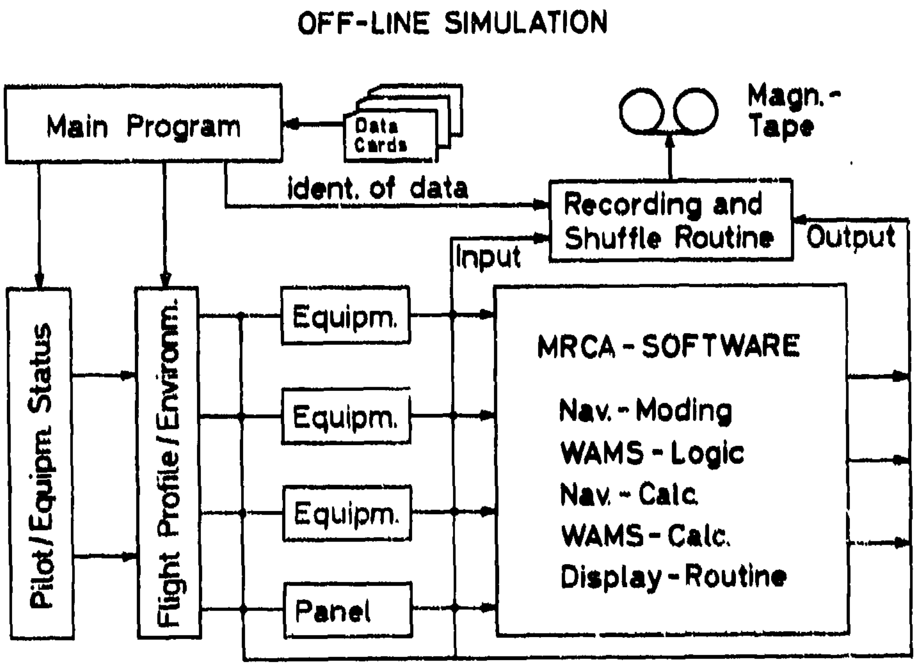


Fig.9 The dual flight simulation of IABG – an example for the systems engineer's tool for predesign and assessment



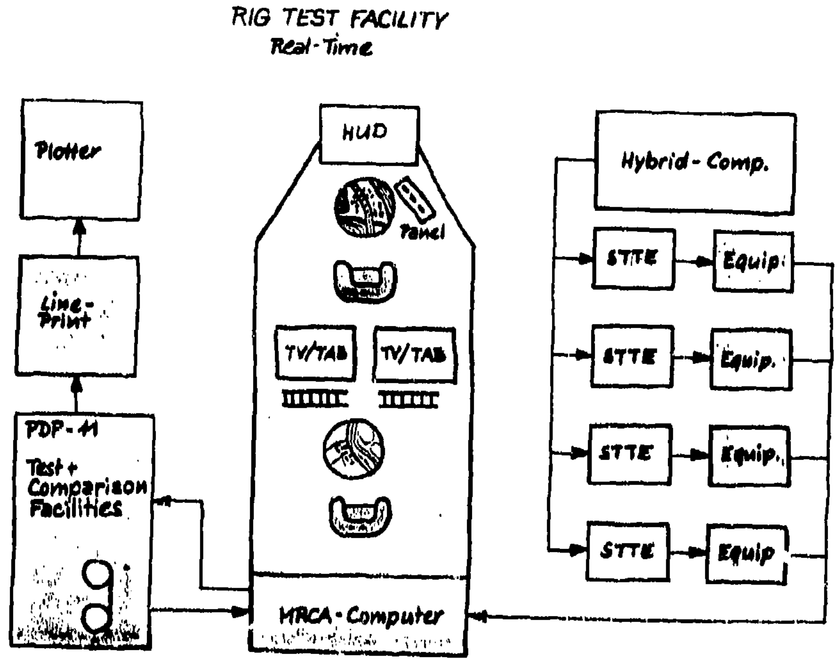
by courtesy of MBB

Fig.10 Simulation during the development -- iron bird: the flight control test rig of MRCA



by courtesy of ESG

Fig.11 Simulation during development



by courtesy of ESG

Fig.12 Test of avionic equipment

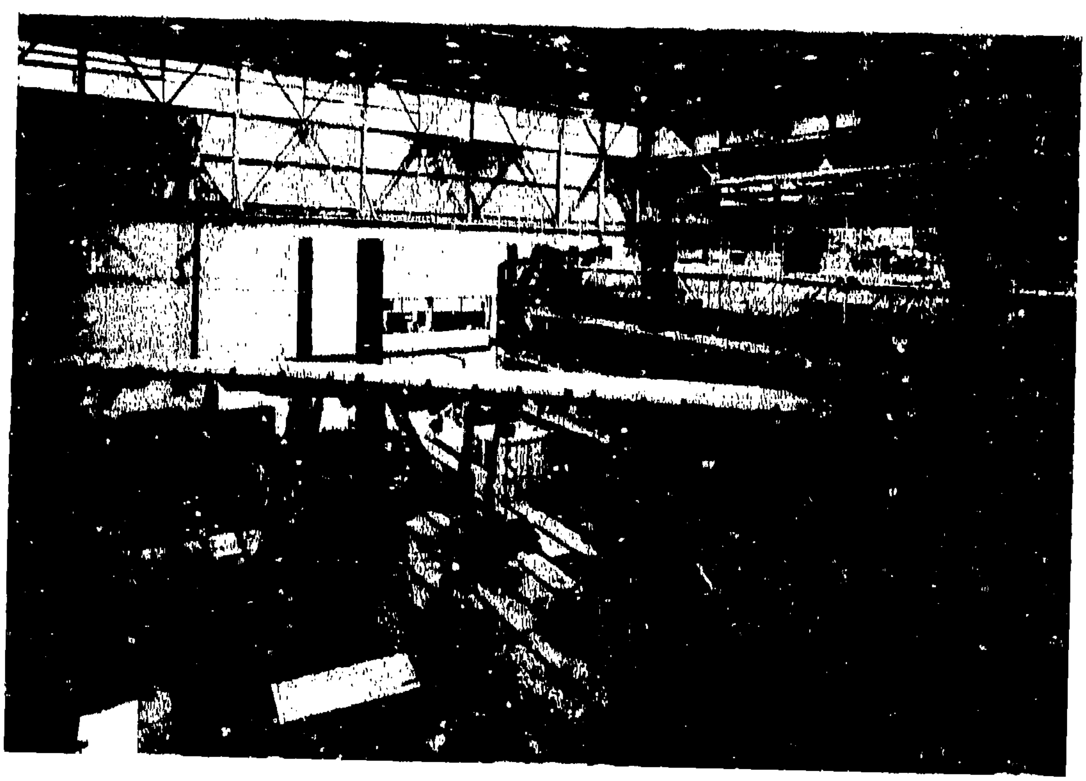
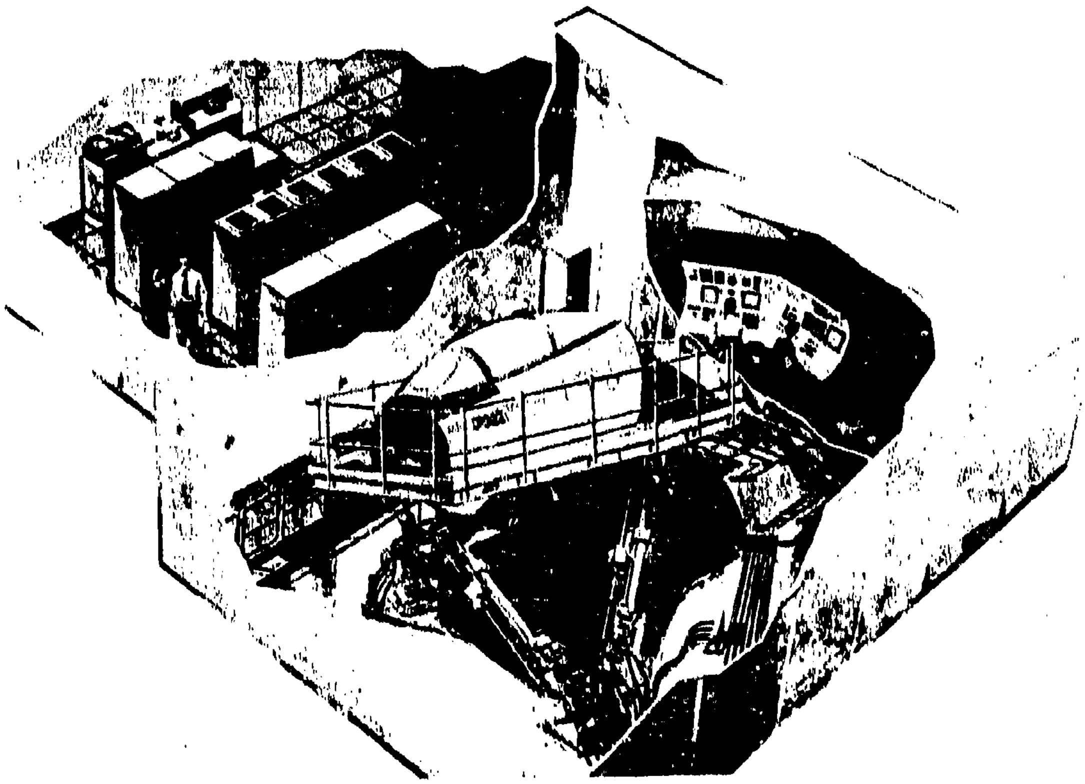


Fig.13 Fatigue testing of a modern civil jet aircraft (Airbus A300) simulated air loads



[courtesy Link - Singer]

Fig.14 Cockpit operational flight trainer

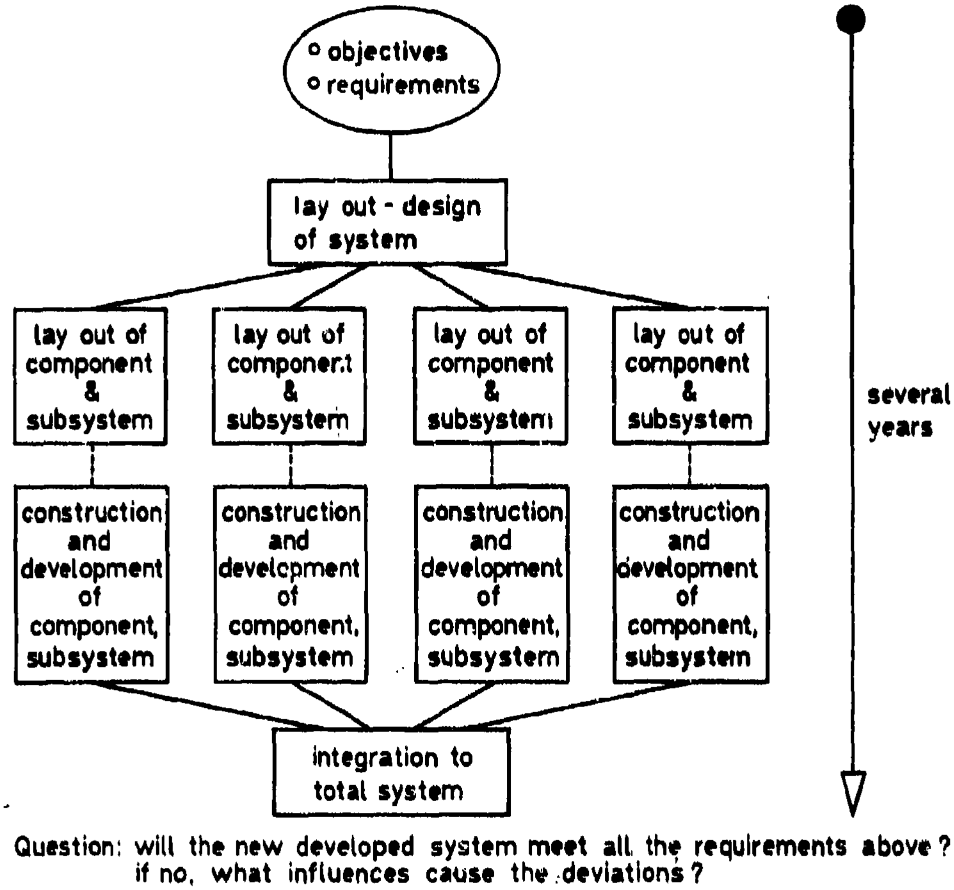


Fig.15 The steps of developments — a simplified version

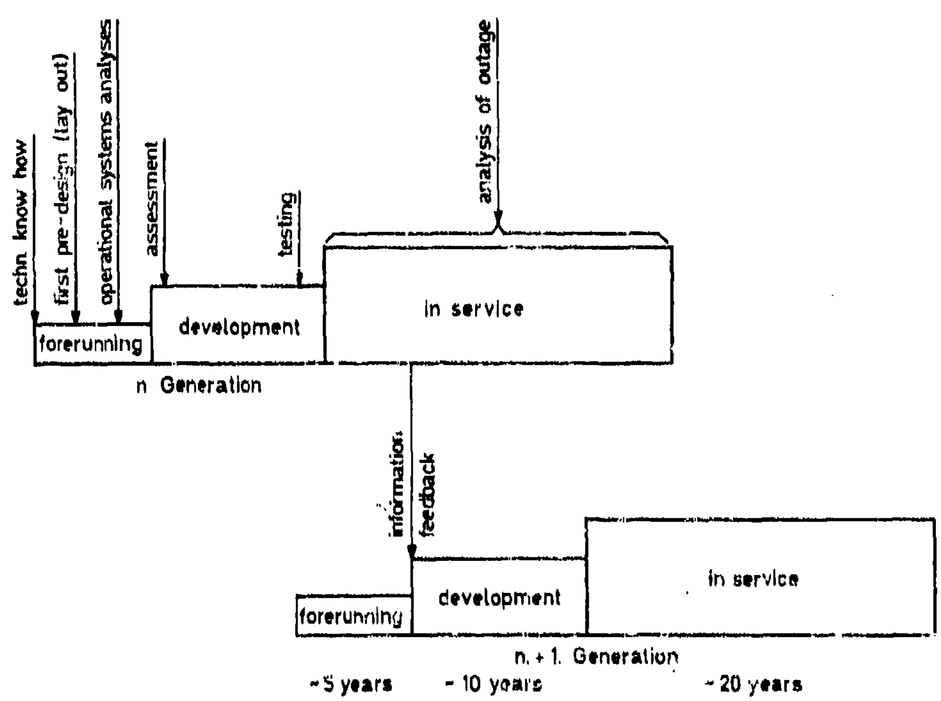


Fig.16 Life cycle of one weapon system's generation

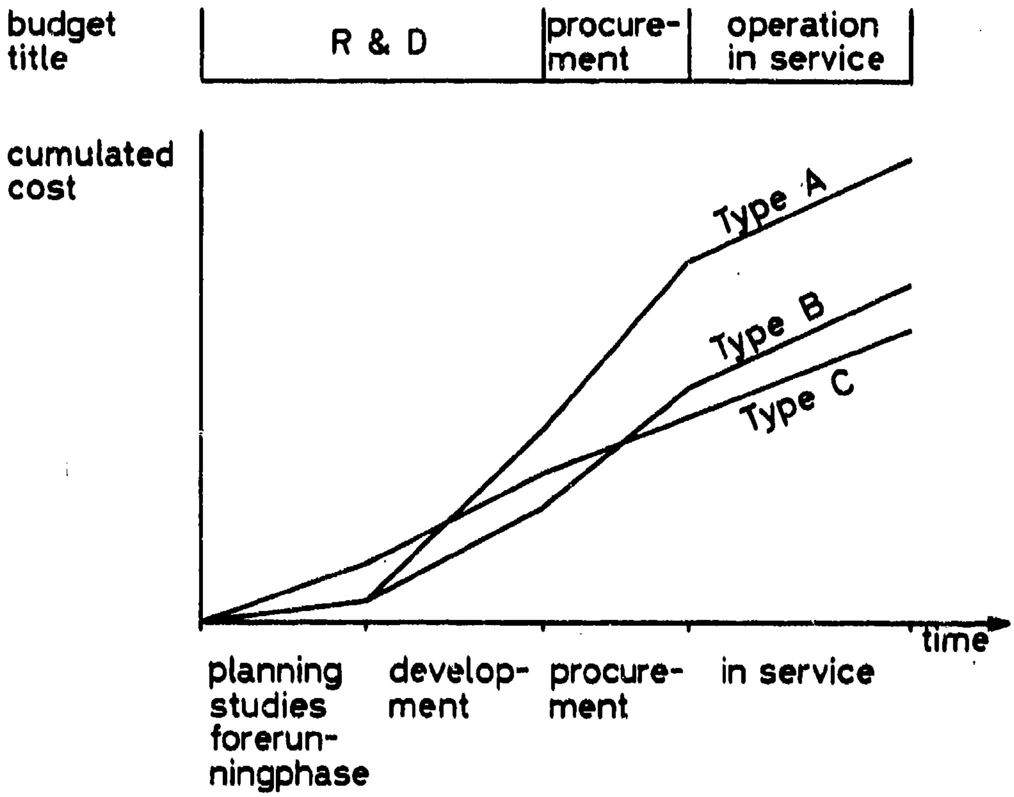


Fig.17 Life cycle cost

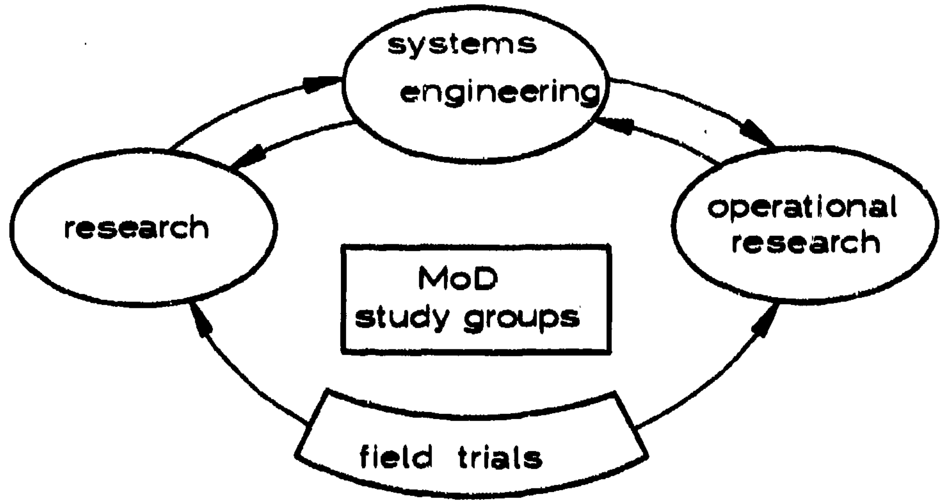
A) Performance Number
of the single weapon-system unit

- o performances
- o effectiveness
- o single unit price
- o cost effectiveness

B) Defense capability

- o weapon systems in combination
- o quantity per every typ
- o tactics
- o total budget

Fig.18 Objectives of the planning process different criteria



after [27]

- alternative, parametric predesigns of future weapon systems
- technical feasibility
- systems integration / computibility
- sensitivity of technical parameters

Fig.19 The instruments for planning support

systems analysis

is a heuristic method
by which components - still unknown at the beginning of the investigation - interdependencies and the behaviour of a system are determined in that way of a successive approach.

It is a strategy of determination - step by step - of systems which shall be explained or designed
whereby the interdependencies between the subsystems are taken into account
already at the beginning of the investigation

after [28]

Fig.20 Systems analysis a definition

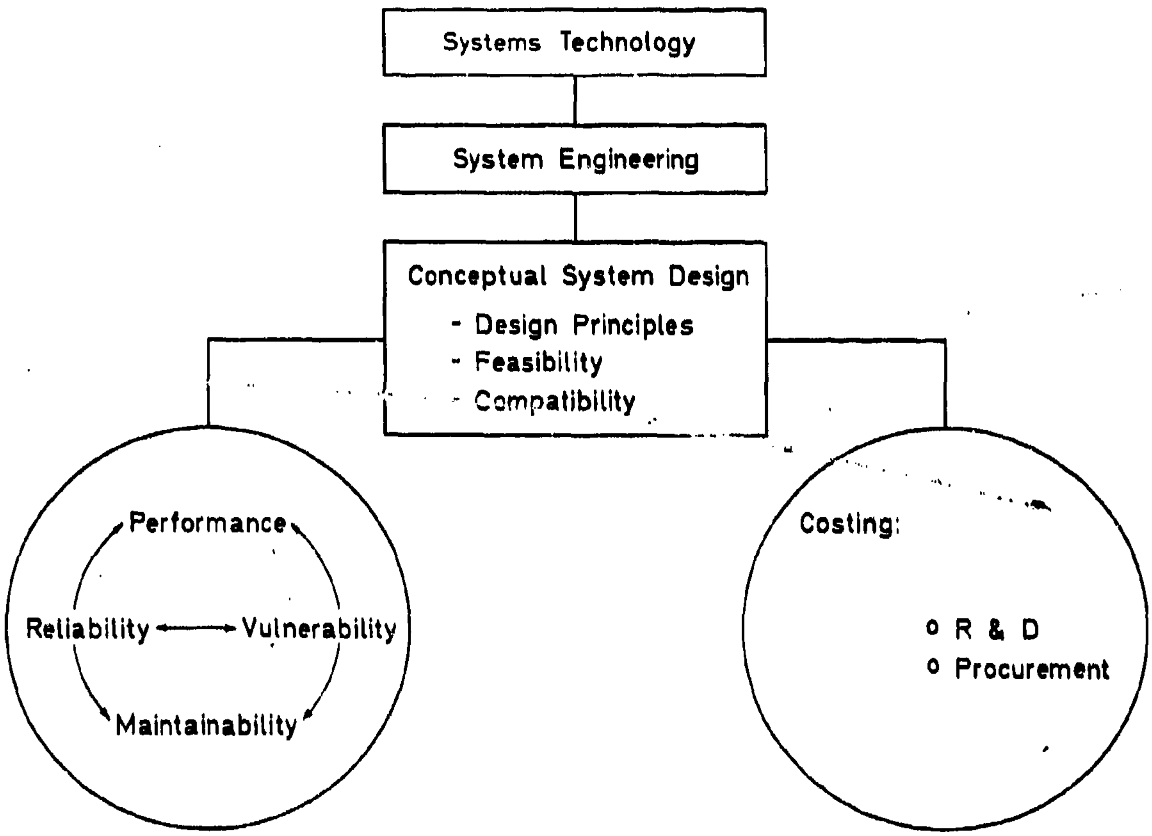


Fig.21 Systems engineering -- the conceptual system design as connecting link between performance/reliability/maintainability and costing

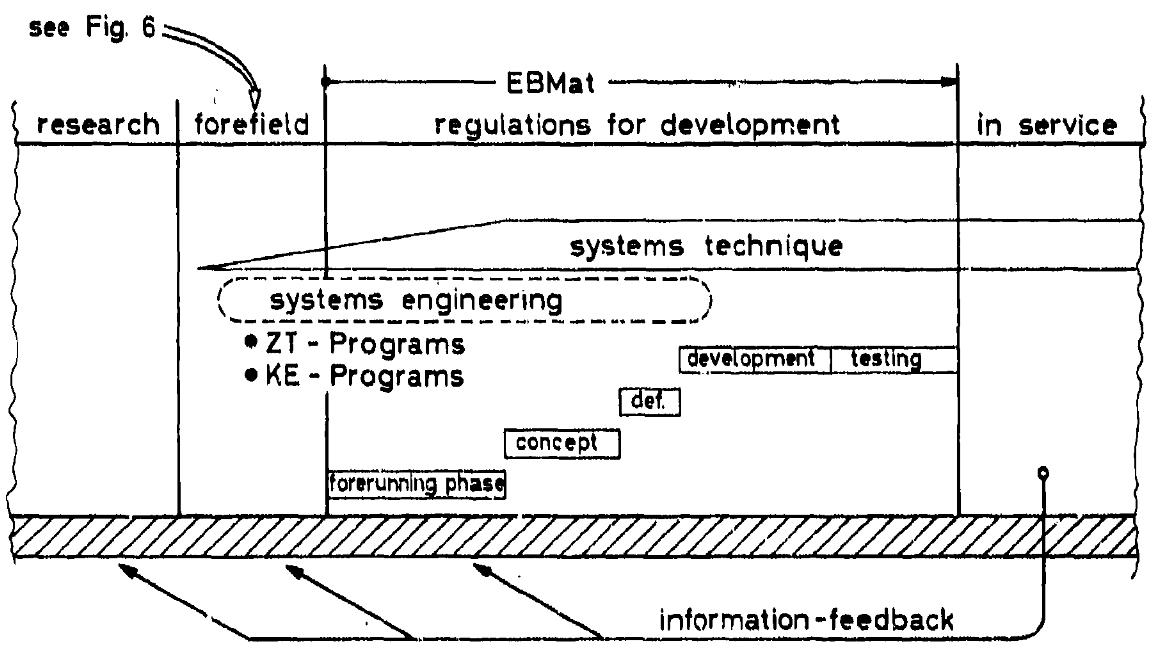


Fig.22 The sequences of activities for providing a weapon system (from research to the final product)

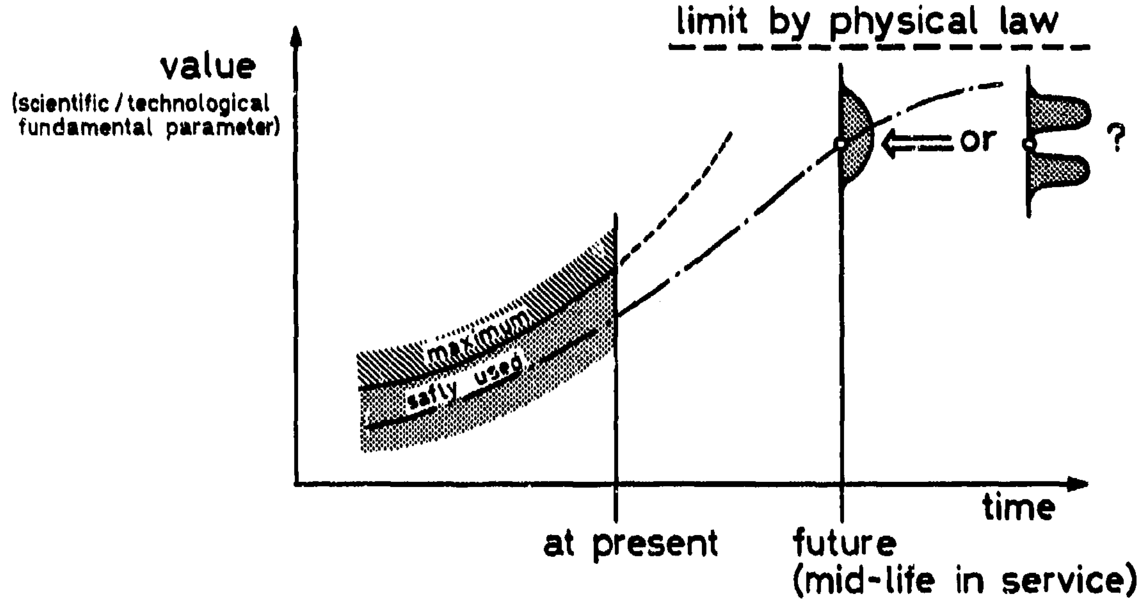


Fig.23 The problem in forecasting the trend of a scientific/physical/technological parameter

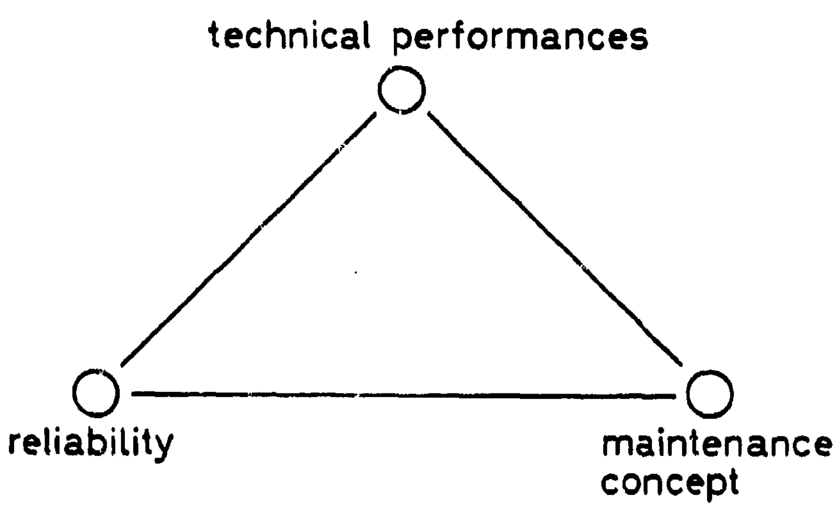


Fig.24 Interrelationship - possibility of substitution between these three quantities

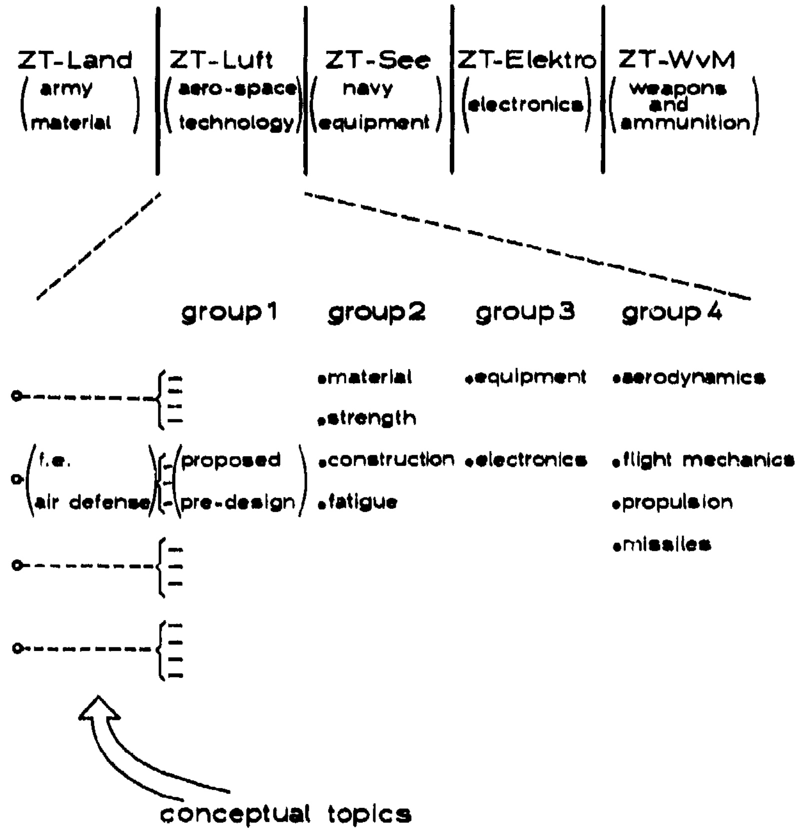


Fig.25 The future technology programs for and on behalf of the G MoD

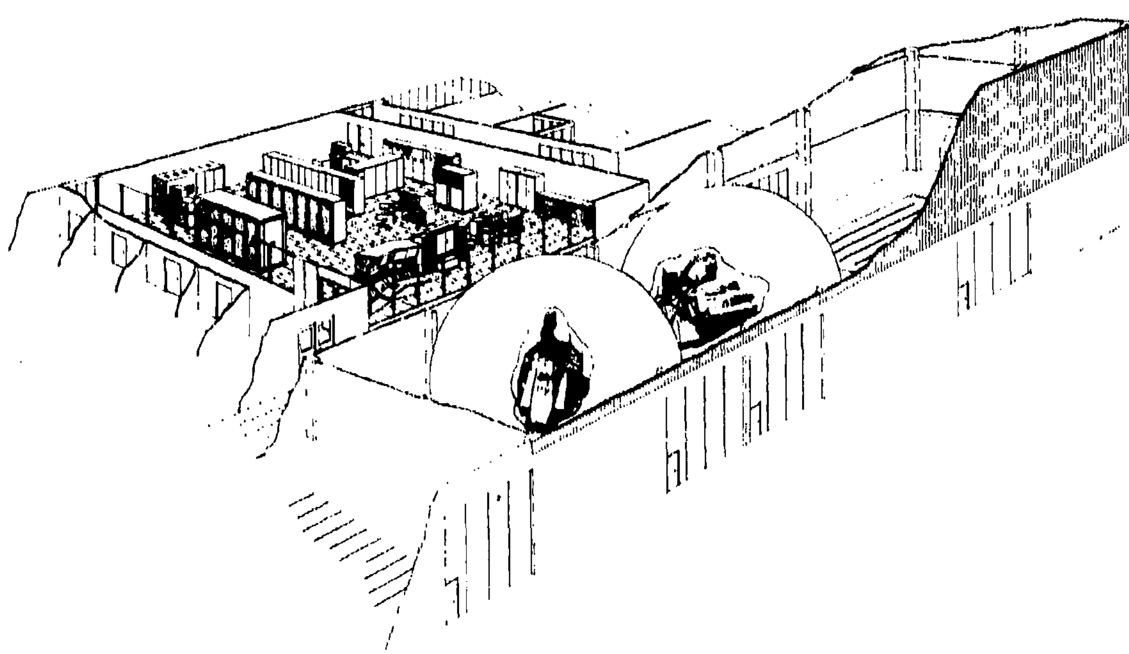


Fig.26 The simulator centre of IABG established for FRG MoD

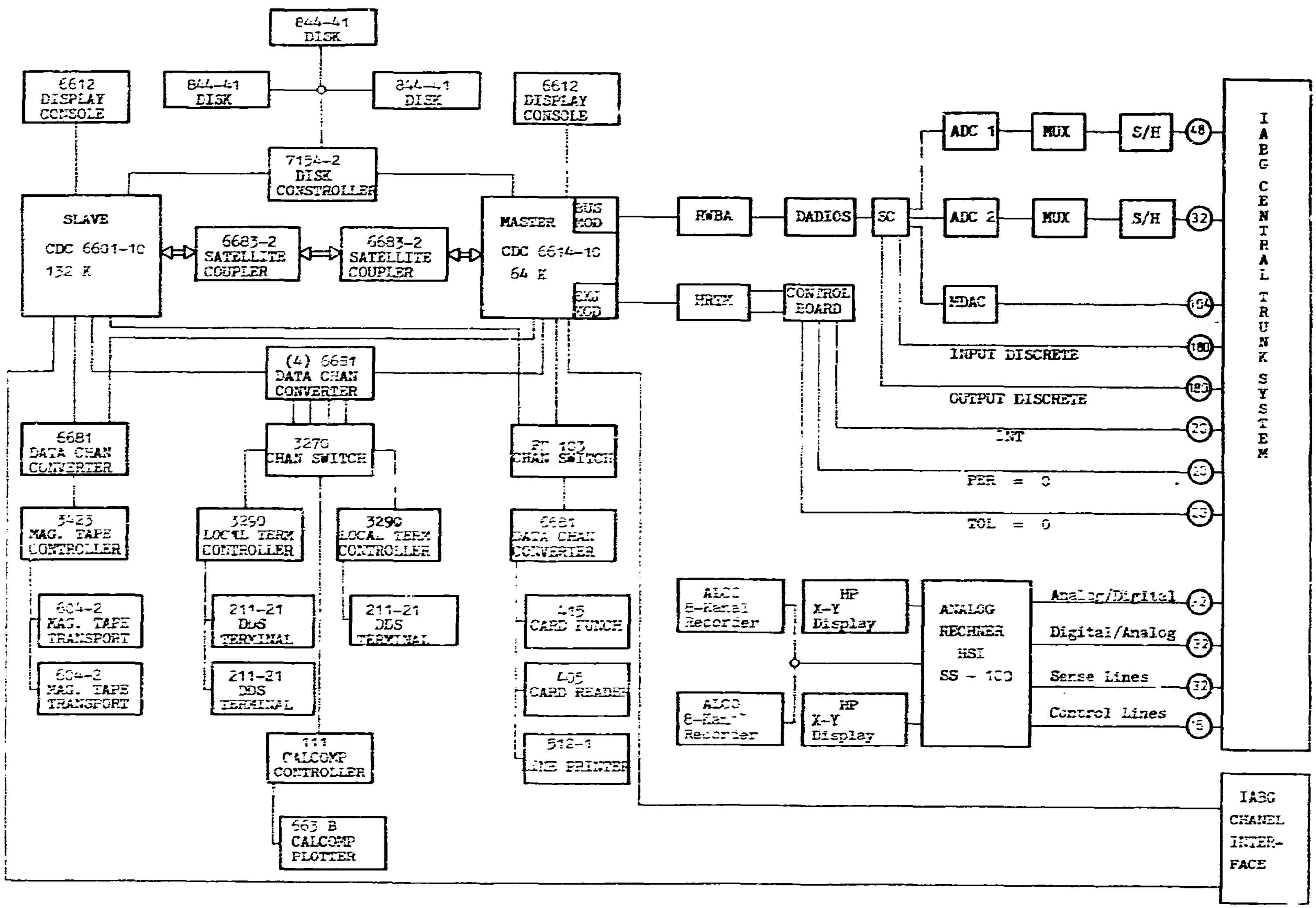


Fig.27 Configuration of a computer specialized for simulation

research		techn. Universities		
		FGAN	FAT	fundamentals ergonomics
			FFM	principles of RADAR
		DFVLR	Institut für Flugführung Institut für Dynamik der Flugführung Institut für Flugfunk und Mikrowellen	vehicle dynamics
		Flug med. Institut Luftwaffe		physiology
forefield activities	planning assessment	IABG	systems engineering OR establishment	
	future technology	industrial enterprises		vehicle mobility flight mechanics missile guidance
	other	Battelle		vehicle mobility
development		industry firm	AEG ESG Siemens ⋮ Do MBB VfW ⋮ Krauss Maffei MaK ⋮	development simulations for various systems of weapon systems (hardware - development)
testing		MoD BMW E-Stellen IABG (industry firms)		
training		F-4 α-jet MRCA	military UH-1D	gunnery simulator submarine C&C simulator [civil DLH]

Fig.28 Use of simulation/simulators — national capabilities and application — (examples; not complete)

- pattern recognition
- sensor performance
- data processing
- resistance to counter measures
- artificial intelligence

Fig.29 Important, evolutionary branches in avionics and C³

- simulation is world-wide proofed and accepted
- simulation is widely used in science and engineering
- the degree of effectiveness by use of simulation is high
- cost-effectiveness in relation to the project investigated is normally high
- in several cases simulation is absolutely the one and only instrument to provide for investigation results
- simulation is technically used in most modern matter
- nevertheless simulation must be in adequate correlation to real world
- this demands for a high degree of simulation technique
- the application of simulation will / must be improved in future; simulation tasks will be more complex
- therefore budgetary conditions must be improved

Fig.30 Conclusions

REPRESENTING HUMAN THOUGHT AND RESPONSE IN MILITARY CONFLICT SIMULATION MODELS

Dennis K. Leedom
Tactical Systems Division
Assistant Chief of Staff, Studies and Analyses
Headquarters, United States Air Force

Abstract

The analysis of command and control system utility requires an understanding of the human component in such systems. This is because command and control systems serve to support various tactical decision processes. Research findings from cognitive science have recently suggested various theories concerning decision processes which may be of use to the developers of conflict simulation models used in command and control analysis. Two approaches to representing decision processes in simulation models are the use of human gamers and the use of computer science decision models. One method for exploiting the advantages of each simulation approach is the development of a command and control testbed. Such a testbed could use both human gamers and computer science decision models in an iterative fashion to evolve a better understanding of the human component in command and control.

Introduction

This paper deals with the subject of conflict simulation models and the representation of human thought and response in such models. The ideas presented in this paper relate to the modeling of conflict situations from single combat unit level up through theater force level. In particular, the author focuses upon the use of such models for assessing the utility of tactical command and control (C^2) systems.

The author first provides a discussion of why explicit representation of human decision processes is important in conflict simulation models used for C^2 systems utility analyses. Next, the author illustrates various decision theories and concepts from cognitive science and behavioral research. While not providing a complete description of how to represent decision processes, this discussion suggests important aspects of decisionmaking which should be of interest to model developers.

Citing illustrations from two different USAF simulation efforts, the author presents and contrasts two approaches to representing decision processes in conflict simulation models. The two approaches are summarized as follows:

> Utilize human gamers to simulate commander/staff decision processes via man-machine interfaces with a computer-driven conflict simulation model.
>
> Utilize rule-based production systems and other knowledge engineering techniques to directly simulate limited aspects of commander/staff decision processes within the conflict simulation model.

Finally, the author suggests the need to combine both decision modeling approaches into an experimental testbed. Such a testbed could extend cognitive research into a realistic, applied environment and provide a means for studying information flow and decisionmaking in tactical C^2 systems.

Performance Measures Versus Utility Measures of C^2 Systems

At the outset of this discussion, it is important to establish some rationale for the interest in human decision processes. To do this, it is further necessary to draw a distinction between two output measures of interest in most analyses of tactical C^2 systems. These measures are defined here, as follows:

> Performance Measure - a specific measure of the C^2 system's capability to perform its own internal activities, without regard to the consequences of those activities. For example, a performance measure of a C^2 system might be defined as "message transmittal rate", "data storage capacity", or "display update frequency".
>
> Utility Measure - a specific measure of the C^2 system's contribution to the total effectiveness of the associated combat force. For example, a utility measure might be defined as "the effect that the C^2 system has on improving the combat force's ability to locate and destroy enemy tanks".

It can be seen that performance is measured inside the C^2 system while utility is measured outside of the C^2 system. Viewed another way, performance relates to the technical capabilities of a C^2 system while utility relates to how those capabilities are exploited so as to improve the effectiveness of the combat force.

Now why is this distinction important? The distinction is important precisely because it is utility, and not performance, which justifies the acquisition of C^2 system hardware. A particular communications system or data management system might perform very well in a technical sense. If,

however, the technical capabilities cannot be exploited so as to support improved C^2 functions, the system hardware has not been justified. In the worst possible case, the system hardware might prove to be dysfunctional and actually degrade C^2 functions.

While this distinction between utility and performance seems obvious, it is sometimes lost by those attracted to the promise of new technology. For example, a new communications system which is capable of exceedingly high data transmittal rates may prove useless (or even dysfunctional) if the recipient of that data cannot effectively absorb or reasonably make use of it. A particular data management system may be able to store and retrieve an impressively large number of facts concerning the conflict situation. If, however, these facts are not organized and presented in a form which provides the commander with information relevant to his decision process, the data management system may be essentially ignored.

This brings the discussion to the expressed interest in explicitly representing human decision processes in conflict simulation models. Except for those C^2 systems which support automated weapon delivery or other automated combat functions, most tactical C^2 systems exist to support human decision processes. These decision processes, in turn, make up the perception, assessment, planning, directing, and controlling activities which guide the deployment and employment of combat forces.

The commander/staff decision processes serve to take the combat information provided by the C^2 system and produce control directives for the combat units. The generic process occurs at each level within the command hierarchy. Hence, the degree to which the technical capabilities of a C^2 system (performance) translates into combat force effectiveness (utility) largely depends upon the human decision processes which intervene at each level within the command hierarchy. If the technical support provided by the C^2 system is not matched to the particular human decision processes at a given command level, then the C^2 functions and resulting force effectiveness are likely to degrade.

Any analysis of C^2 system utility should include an investigation of the various human decision processes supported by that system. This requirement is reflected in the key questions which emerge in this type of study:

> What are the key combat decisions to be supported by the C^2 system? That is, what major options are available to the decisionmakers involved, what critical conditions must be achieved (or avoided), and what are those points in the dynamic flow of the conflict where critical choices must be made and carried out?
>
> For each key combat decision, how is the decision likely to be made? Are the key decisions instantaneous, or do they emerge gradually through stepwise commitments to an idea or plan? Is the decision process highly structured with known alternative courses of action? Or is the decision process somewhat unstructured because of certain unique features of the situation? How does the decision process account for uncertainty?
>
> What types of information are considered relevant to each key decision process? What types of information strongly influence the structuring and outcome of each decision process? What types of information only moderately influence each decision process?
>
> What contribution does the C^2 system make to each key decision process? Does the C^2 system provide the decisionmakers with relevant information in a timely manner? Does the C^2 system allow the decisionmakers to sequentially refine their information requests or obtain additional information, as necessary?
>
> Given the range of possible decisions which could be made at each critical point in the conflict, what difference do "good" decisions make? What is the range of possible consequences at each critical point? What subset of consequences is attainable because of the support provided by the C^2 system?

In addressing these types of questions, the analyst attempts to understand how the C^2 system serves the particular needs of the associated decisionmakers. The form of this research can be either descriptive or normative, depending on the type of C^2 system under investigation. For existing C^2 systems, the analyst is most likely attempting to describe the current manner in which the system is used. For proposed additions or modifications to a C^2 system, the analyst is probably more interested in exploring ways of improving the decision processes.

One tool available to assist the analyst in C^2 system research is the simulation model. Such models must, however, portray an accurate representation of both technical and human elements within a C^2 system. The simulation of most technical elements in a C^2 system is relatively straightforward, given the model developer is provided with sufficient details of these elements. In contrast, the simulation of human elements has presented a great number of problems for the model developer.

As compared to questions of technical performance, model developers have found most aspects of human behavior difficult to structure and represent in quantitative terms. But wherein lies the difficulty? Are the complexities of human behavior and thought processes completely resistant to systematic understanding and modeling?

To some, the answer to this last question appears to be "yes". Accordingly, many analysts have largely ignored human elements by adopting one or more of the following simulation approaches:

> Assume the C^2 system operates so as to always maximize the combat effectiveness of the force.

Assume that the combat forces operate according to fixed procedures and/or scripted scenarios.

Account for C^2 errors or limitations by assuming degradation factors for combat force effectiveness.

Another group of analysts have chosen to utilize human gamers to simulate decisionmakers via man-machine interfaces with their computer-driven conflict models. In taking this approach, these analysts have concluded that human elements can, at best, be represented as "black boxes". That is, they choose to merely use the results of these decisionmakers rather than attempting to understand how they operate.

Yet another group of analysts have aligned themselves with the fields of computer science and knowledge engineering in an attempt to directly model human decision processes. To many of these analysts, nothing is beyond the realm of mathematical description.

Hence, within the past several years, a great debate has arisen among those who would ignore human behavior in models, those who would say human behavior must be represented by real people, and those who claim human behavior is susceptible to mathematical description. Who is right? Who is wrong?

In an attempt to shed light on this debate, the remainder of this paper is devoted to discussing the general nature of tactical decision processes and to contrasting the strengths and limitations of using human gamers versus mathematical models to simulate such processes in conflict simulation models.

A Brief Survey of the Cognitive and Behavioral Sciences

The cognitive and behavioral sciences are rich with research pertaining to various aspects of human decision processes. This research extends from the elementary or neural level of information processes to the level of higher mental activities for both individuals and organizations. The past five or six years has seen a rapid burgeoning of information processing models of cognition and even computer simulations of these models. [SIMON, 1979] Hence, it would seem natural for those analysts studying C^2 systems to take advantage of what has been learned in the cognitive/behavioral fields.

Because of the wealth of material which has emerged from these fields, no paper of this length could begin to present a complete discussion of human decision processes. It is important, however, to briefly survey a few key concepts which may assist the development of improved simulation techniques. The discussion of these concepts focuses on the following general questions:

Should we view man as completely rational in his decisionmaking, or are there other, more appropriate descriptions of his behavior?

Should we view man as exhibiting only one type of decision process, or are there several types of decision processes involved?

Is it possible to state a general model for human decision processes?

Is man completely rational?

In their book on decision support systems, Keen and Scott Morton describe what they consider to be five main perspectives on decisionmaking. [KEEN, 1978] They are

the rational view of decisionmaking,

the "satisficing" and process-oriented view of decisionmaking,

the organizational process view of decisionmaking,

the view of decisionmaking as a political process, and

the individual differences view of decisionmaking.

The rational view of decisionmaking stems from the classic theory of microeconomics where man is assumed to be completely rational, well-informed, and capable of matching utility preferences against a precisely defined goal or objective. This view of man as a rational and explicit decisionmaker aligns itself closely with the traditional field of systems analysis. However, many researchers reject this view as being too impractical and ideal. While rationality remains a dominant influence in classical economic analysis, many other areas of decisionmaking are subject to incomplete knowledge, ambiguous utility measures, and imprecise goals. Hence, in many instances, man is incapable of exercising completely rational judgement.

The "satisficing", process-oriented view of decisionmaking focuses on how decisionmakers best use their limited knowledge and skills. Rules of thumb (or heuristics) are said to be employed by decisionmakers in a search for a solution which is "good enough" instead of "optimal". The heuristics are simplified rules of condition and choice which allow an individual to deal with more complex problems and situations.

The organizational process view examines both the decisionmaker and the system within which he operates. This view states that systems (or organizations) evolve standard procedures for dealing with most operations. Decisions within a particular system are largely determined by these standard procedures which constitute its institutional memory and store of knowledge. In actual practice, a system may be made up of many subunits, each with their own set of standard procedures and activities. Hence, this view also stresses organizational roles, relationships, and communication.

The political view stresses the degree of power bargaining associated with many organizational decision processes. Bargaining occurs as the various subunits within a system compete with one another for power and influence. Hence, the contents of many decisions are viewed as less important than the process by which they are made.

The individual differences view of decisionmaking focuses on the information-processing and problem-solving behavior of the individual decisionmaker. Individuals are seen to vary significantly in their ability to deal with problem complexity and information load. One theory argues that there is an optimal level of information input for any one individual and that too little or too much information degrades performance. This view of decisionmaking also stresses the importance of individual cognitive style (analytical versus intuitive) and the need to match information input to that style.

The various theories just presented should not be interpreted as contradictions to one another. Rather, they are more likely to be simultaneously true in varying degrees for any given system or organization. The relative dominance of any one theory would depend upon conditions existing in the particular system under study. For a tactical C^2 system, it is easy to illustrate aspects of each theory.

The rational view of decisionmaking best fits the traditional, doctrinal image of the commander who is supposed to flexibly and optimally employ his combat resources toward the achievement of a prescribed objective. In actuality, the imprecision of many military objectives and the limited knowledge of the commander/battle staff/support staff are likely to produce "satisficing" type decisions. Although it is difficult to elicit the exact heuristics employed in such decisions, the existence of such simplifying rules of thumb is hard to deny.

Standard operating procedures also exist for most aspects of tactical C^2 functions and they can be found recorded in the many operations manuals published by each military service. Although these procedures do not always specify the exact process by which certain decisions are to be made, they do serve as a unifying influence over the tactical C^2 system. Hence, it is possible to predict (with some confidence) the general outcome of many tactical decision processes. Training and field exercises are also seen as a means for refining these procedures and insuring their uniform implementation by the various commanders and staffs.

Anyone who has witnessed inter-service debates over combat roles, missions, and interoperability requirements will not dismiss the existance of political bargaining. The degree to which this bargaining process persists in wartime varies from instance to instance. Evidence from World War II suggests that even close allies are not above such practices.

Individual decision styles for commanders are an accepted fact within the military, even though the relative importance of this notion is not always emphasized in the operations manuals. The classical view of the military holds that a certain amount of intuition and innovation is expected from its commanders. At the same time, most military commanders are a product of schools which stress analytical problem-solving styles. Clearly, there is need for both intuition and analytical thought; but, the exact role played by each in combat is a function of the individual.

<u>Does man exhibit only one type of decision process?</u>

Much of the basic cognitive research to date has focused on the mechanisms involved with solving well-structured problems. Models describing such processes have reached a considerable state of development. Research in more complex areas of cognition such as semantic (or long-term) memory, learning, motivation, and emotions have failed to produce similar progress. There is evidence to suggest, however, that the human mind involves more than one type of problem-solving or decisionmaking process.

One concept, referred to commonly as right and left brain processes, distinguishes between verbal/logical/linear processes which are said to occur predominantly in the left hemisphere of the brain and the nonverbal/intuitive/holistic processes which occur predominantly in the right hemisphere. As suggested by Strauch, this distinction is important in many decision or assessment processes. [STRAUCH, 1974]

On the nonverbal/intuitive/holistic level, the brain deals with concepts, spatial relationships, and analogies as a whole process or Gestalte. It is at this nonverbal level where intuition operates, arational thought occurs, and feelings or emotional values find significance. It is also at the nonverbal level where decisionmakers construct their own "internal model" of the problem situation or environment.

On the verbal/logical/linear level, the brain deals with language and its literal meaning. Language as defined here includes both natural language (such as English or French) and mathematical language (numbers, symbols, and functions). Hence, it is at the verbal level where communication with other humans takes place. Speech, mathematics, logical argument, and quantitative analysis all belong to the verbal processes of the brain. The digital computer (with its mathematical/logical foundation) is merely an external extension of this verbal thought process.

While these two levels of thought are complementary to one another, they are still distinct processes. Hence, we are unable to precisely define nonverbal/intuitive/holistic thoughts in verbal terms. For example, we often find it difficult to verbally express a precise notion or internal image. Conversely, as we listen to others verbalize an idea, we can suddenly produce a "flash of insight" as our nonverbal thought process discovers a familiar paradigm or image. Image communication can often transmit ideas which are difficult or impossible to verbalize (such as "a picture being worth a thousand words").

Perhaps, a more profound implication for the systems analyst is that we are limited in our ability to mathematically model nonverbal decision processes. Mathematics, itself being based upon left brain thought processes, may inherently be incapable of representing right brain thought processes. If so, this conclusion has great significance for the simulation model developer. Indeed, we might have to

await the development of a completely different computer (one based on image processing) before we can successfully model aspects of right brain activity.

To complete this discussion of the various modes of thought, it is interesting to review what Soviet authors have to say about this subject. In their book on decisionmaking and automation, Druzhinin and Kontorov suggest that decisionmaking involves several modes of thought, depending upon the complexity and uniqueness of the problem situation. [DRUZHININ, 1972] These modes are defined as follows:

> Empirical thought - orientation and reaction according to simple, ready-made patterns. The observed problem situation is identified with a paradigm stored in memory. In response, a stereotypical reaction is selected and realized. Empirical thought represents the accumulation, systematization, and organization of experience.
>
> Axiomatic thought - reaction according to a system of rules (or axioms). The observed problem situation is tested through the application of appropriate rules. A response is logically derived from the application of these rules. Each rule reflects a concentration of social experience which is held to be true by the decisionmaker.
>
> Dialectic thought - the detection and resolution (or synthesis) of a basic contradiction in the problem situation. Dialectic thought represents a threshold transition or qualitative jump to a new creative idea. It is a process which occurs unconsciously.

Stored knowledge and pattern recognition are both involved to varying degrees in each mode of thought presented by the Soviet authors. Empirical thought makes the most rigid use of stored knowledge and pattern recognition while dialectic thought makes the most flexible use of each. A decisionmaker is capable of employing each mode of thought, usually selecting one on the basis of the degree of familiarity and complexity in a given problem situation.

In comparing the Soviet views with those of verbal and nonverbal thought, one sees some similarity. For example, axiomatic thought involves predominantly verbal/logical/linear processes while dialectic thought involves predominantly nonverbal/intuitive/holistic processes. Empirical thought may involve either verbal or nonverbal processes, depending upon the degree to which experience has been assimilated into the subconscious (a reflex).

Is there a general model for decision processes?

As mentioned earlier, much of the past cognitive research has focused on problem-solving models for well-structured tasks. That is, the problem space or domain is assumed to be fairly well conceptualized by the decisionmaker. In addition, these problem domains were relatively simple and required little, if any, specialized knowledge.

Recently, this work has been expanded into semantically rich problem domains. [SIMON, 1979] A semantically rich problem domain is one which requires specialized knowledge, as well as for general problem-solving skills. Much of this recent work has focused on the organization and storage of "expert knowledge" in long-term memory.

A significant view which has emerged from this research is the concept of the "production system". A production system is a set of instructions called productions. Each production involves a condition statement and a corresponding action. The action (which may be a conclusion or judgement concerning some aspect of a problem) is executed whenever the condition is satisfied. Conditions generally relate to some feature of the problem domain.

Recent experience with studying decisionmaking in chess, medical diagnosis, and other specialized knowledge fields suggests the importance of production systems in storing "expert knowledge". The condition-action pair in productions have been related by some researchers to the stimulus-response theory. Unfortunately, historical experience suggests that it is often difficult to extract expert knowledge from people in a systematic manner. Considerable interaction between the expert and the analyst is required to elicit a robust set of productions from people who are not used to consciously thinking about their own problem-solving heuristics. [WATERMAN, 1977]

A second branch of problem-solving research has dealt with problem understanding or description. Unlike the well-structured problems studied by many earlier researchers, problems in real life are not always well defined. Hence, before specific knowledge and problem-solving procedures can be employed, a decisionmaker must often first determine what kind of problem is faced.

Some psychologists have defined this initial step as an attempt to resolve ambiguities in the decisionmaker's perceived environment. That is, a decisionmaker must first make sense of his situation before he can propose and assess alternative courses of action. In "making sense" of his situation, the decisionmaker is comparing his perceived environment with previously stored experiences. In doing so, he is seeking to recognize analogies or problem isomorphs which will either suggest a solution to him or, at least, define the nature of the problem he is faced with.

Accordingly, a decisionmaker will seek additional information about his environment (or will test his environment) in order to resolve any remaining ambiguities in his perception. Only at the point where further problem resolution is impractical will the decisionmaker rely on pure judgement.

Several authors have suggested that it is important to capture this aspect of the decision process in any attempt to model decisionmaking. Dreyfus and Dreyfus discuss this environmental perception step in their informal model of decisionmaking. [DREYFUS, undtd] They contrast the need to first establish the context-dependent aspects of the situation with the contrary assumption in formal decision models that these aspects are already known.

A second pair of researchers, Aldrich and Levit, describe much the same idea in their development of "frame theory" as a model for decisionmaking. [ALDRICH, 1978] In this latter work, based on a concept by Minsky, these authors describe how decisionmakers seek to establish a framework for each problem. [MINSKY, 1975] Each framework (or action frame) contains the following unique procedural information:

Activation conditions which determine when to adopt the frame

Types of information needed to support the decision process

Procedures for developing alternative solutions

Procedures for evaluating alternative solutions

Procedures for selecting among the evaluated solutions

Procedures for implementing the selected solution

Keen and Scott Morton also allude to a similar concept when they discuss the degree of "structure" associated with a given problem situation. "Structure," as defined by these authors, predetermines the problem-solving procedures to be invoked, the types of computation and analysis, and the information to be used. Unlike their "rational" decisionmaker who approaches every problem in the same manner, Keen and Scott Morton suggest that problems can vary significantly in structure (or be unstructured). Hence, decision processes are highly variable, depending upon the degree and type of problem structure perceived.

For simulation model developers, these various research findings suggest that most decision processes can be viewed as a two-stage activity. In the first stage, the decisionmaker is attempting to define his environment and identify the context in which he is to make a decision. Having identified this context (or structure), the decisionmaker then invokes a predetermined set of problem-solving procedures or heuristics to arrive at a desired course of action.

For decisions involving uncertainty and risk (a characteristic on many tactical combat decisions), production systems and frame theory may prove to model human behavior very closely. Recent investigations of decisionmaking under uncertainty suggest that humans systematically violate the principles of rational thought when attempting to assess likehood, make predictions, or otherwise deal with probabilistic tasks. [SLOVIC, 1976] The notion that heuristics and biases significantly influence probabilistic judgements has gradually replaced the concept of Bayesian behavior in humans. These heuristics and biases are based on perceived similarities of events and processes, familiarity of events, and the adoption of initial perceptions or judgements.

Before concluding this topic, it should be pointed out that there may still exist aspects of decision processes which are not completely described by two-stage activities and production systems. The earlier discussion of nonverbal/intuitive/holistic thought suggests that the brain is capable of image processing, as well as symbol processing. The general subject of pattern recognition (which is key to frame theory) involves aspects of semantic memory which have not clearly been defined.

Thus, in reviewing the existing research, one is capable of constructing only a partial model of decisionmaking. Increasing interest in this field of science, however, suggests that future research will add to our understanding and modeling of decision processes.

An Illustration of Each Simulation Approach

The discussion now turns to the alternative approaches defined for representing human thought and response in conflict simulation models. To illustrate the essential characteristics of each approach, examples of their application to two different USAF simulation efforts are briefly highlighted. These two examples illustrate the simulation of essentially the same conflict situation. A principal difference between the two simulation models is the method used to represent human decisionmaking.

Tactical Air/Land Operations Simulator (TALON)

TALON is an interactive simulation model of combined air/land combat operations. [USAF/TFWC, 1978] It is essentially a computerized extension of a manual war game, with tactical decisions reserved to human gamers and all bookkeeping tasks performed by the computer. The original version of TALON was introduced as a USAF methodology by the Assistant Chief of Staff, Studies and Analyses. Continued development responsibility has now been transferred to the USAF Tactical Fighter Weapons Center.

TALON portrays (in its present form) a two-sided, theater or corps-level ground conflict situation along with the associated air strike and reconnaissance operations provided by a tactical air force. Ground unit resolution depends upon the scale of conflict selected (e.g., battalion-level resolution is provided for a corps-level conflict).

The TALON ground war module simulates movement and attrition of maneuver/supporting ground units. Ground combat attrition is derived from modified Lanchester equations calibrated to the results of micro-simulations of battalion-level operations. Unit strengths are expressed as "tank equivalents" to provide the human gamers with an intuitive notion of each unit's potential killing rate against enemy units.

Air strikes (close air support and interdiction) are not modeled in their entirity. Instead, the TALON air attack module focuses on the end-game details of ground target acquisition and air munitions effectiveness. Air attacks against ground units serve to reduce unit strength and cause movement delays.

Air reconnaissance operations simulated by TALON include both data-gathering and data-fusion activities. The data-fusion activity provides a consolidated perception of the battlefield for the human gamers. The accuracy and completeness of this perceived picture of the battlefield is a function of the frequency, coverage, and quality of the airborne reconnaissance sensors portrayed in TALON.

Gamer interactions with TALON are depicted in Figure 1. Tactical decisions provided by the human gamers are organized according to air strike planning, ground operations planning, and reconnaissance mission planning. Those tactical decisions are input to TALON at predetermined intervals during the execution of the simulated conflict.

Air strike planning involves matching available air sorties to specific enemy ground targets. Ground operations planning includes the specification of path-points for unit movement and the assignment of fire support to maneuver units. Reconnaissance planning involves the scheduling of sensor overflights for enemy target areas of interest.

Through interactive graphics displays and a sequence of structured questions/responses, the TALON gamers can request a variety of information displays and input a variety of planning decisions. Information is displayed in both tabular and map form. This offers the gamers a variety of information sources and formats to assist them in forming a perception of the conflict situation.

For air strikes, TALON offers an automatic sortie allocation feature which relieves the gamers of this decision task. The automatic allocation may be overridden by the gamers, if they so desire. For ground operations, unit path-points are generally prespecified at the beginning of the simulation run. Adjustments to these movement plans may be input, however, if warranted by the conflict situation. Reconnaissance flights may be scheduled individually or recursively throughout the simulation run.

Great emphasis is placed on the use of human gamers within TALON. Although specific elements of the ground and air command hierarchies are not represented, the consolidated gamer team is exposed to the general perceptions and problem situations faced by real planning staffs. The lack of a detailed C^2 system architecture in TALON prohibits its use for studying issues involving distributed decision processes. The model does provide, however, an opportunity for the human gamers to use their total cognitive capabilities to influence the course of the simulated conflict.

To date, TALON has been employed in support of various studies dealing with combined arms operations. TALON's utility has been demonstrated by the first-order insight it provides to issues involving the value of air strike and reconnaissance resources and the synergism between land and air forces.

TAC ASSESSOR

TAC ASSESSOR is also a simulation model of combined air/land combat operations. [USAF/SA, 1978] The ground and air operations are simulated in much the same manner as those portrayed in TALON. In fact, both models are derivatives of an earlier simulation model, Tactical Warfare Simulation Program (TWSP). The unique feature of TAC ASSESSOR is the C^2 structure overlaid onto the ground and air combat model. This C^2 structure embodies production systems and other computer science techniques to explicitly represent the tactical decision production processes of the various C^2 elements. Development responsibility for this USAF model resides with the Assistant Chief of Staff, Studies and Analyses.

TAC ASSESSOR portrayes a two-sided, corps-level ground conflict situation plus the associated air missions of close air support, battlefield interdiction, reconnaissance, and defense suppression. Ground combat, air strike, and reconnaissance relationships are essentially identical to those simulated in TALON.

The ground force C^2 structure is explicitly portrayed for corps headquarters down through each battalion headquarters. The air force C^2 structure is explicitly portrayed for each element of a USAF Tactical Air Control System (TACS). These various headquarters and control elements are illustrated in Figures 2 and 3.

Prime emphasis in TAC ASSESSOR is placed on the use of production systems, signature tables, directed relational graphs, and other computer science techniques to model various aspects of tactical decisionmaking. The model user is provided with a generic decision structure for each ground headquarters plus a flexible language with which to create production systems. Figure 4 illustrates this generic decision structure for a typical ground headquarters.

The user may access and modify the production systems for any particular ground headquarters via interactive graphics displays. In this manner, the user may test and refine various heuristics sets which describe the behavior of each headquarters. A typical set of heuristics and corresponding production system are illustrated in Figure 5.

Another decision modeling technique extensively employed in TAC ASSESSOR is the signature table. A signature table extracts important information about a given problem domain by examining meaningful combinations of problem features. This versatile technique (a generalized form of decision logic tables) can be used to represent skilled decisionmakers who focus on combinations of key problem features (called a signature).

Figure 6 illustrates a typical use of signature tables in TAC ASSESSOR. The example shown represents one step in the complex process of updating a perceived battlefield picture when a reconnaissance mission detects a new enemy ground unit. In this step, the newly detected ground unit is compared to

nearby units already identified from previous reconnaissance reports. Here the comparison is made on the basis of observed vehicle types within each unit. The output of the signature table is a subjective assessment of how nearly matched the units are (by vehicle type). Other tables are used in hierarchical form to make other types of comparisons (e.g., unit location and unit velocity). The total set of tables simulate the likely decision process of a skilled intelligence officer determining whether he has detected a new unit or has just seen a previously identified unit which has relocated.

Also simulated within TAC ASSESSOR are the communication nets which link the various headquarters control centers, sensors, and aircraft flights. These communication nets must exist in order for messages and reports to flow among the various decision centers. It is the flow of messages and reports which trigger the individual decision processes throughout TAC ASSESSOR.

To date, TAC ASSESSOR has been used to investigate the extent to which tactical decision processes can be mathematically represented. As such, the model represents a major break from traditional conflict simulation. Its developers will continue to test the behavior of TAC ASSESSOR's simulated headquarters and control centers in an attempt to refine and augment the various decision processes represented.

Advantages and Limitations of Each Simulation Approach

A comparison of simulation models like TALON and TAC ASSESSOR reveals that each simulation approach has relative advantages and disadvantages. Hence, it is not the purpose of this paper to generally favor one model over the other. To explore these advantages and disadvantages in more detail, the discussion focuses on the following attributes of C^2 representation within this class of simulation model:

- Scope and resolution
- Transparency
- Consistency
- Fidelity
- Technical risk

Scope and Resolution

Scope is defined here to mean the extent to which the total C^2 system is represented in the conflict simulation model. That is, how many command echelons of each force component are accounted for in the model? Resolution refers to the level of detail provided for each C^2 echelon represented. That is, to what degree are the individual C^2 elements explicitly portrayed in the model?

Experience suggests that the use of human gamers to simulate tactical decisionmakers is expensive in terms of both facilities and personnel. The limited availability of gaming facilities and qualified personnel will generally tend to restrict the number of places where human gamers interact with the computer simulation. This, in turn, restricts the scope and resolution of the simulated C^2 system since decision processes must be aggregated, simplified, or ignored to correspond with available gamer resources.

The use of computer science techniques to represent decision processes reduces the need for supporting gaming facilities and personnel. Hence, the use of such techniques makes possible (at least potentially) the study of distributed decision processes in large C^2 systems.

Transparency

Transparency is defined to mean the degree to which C^2 processes are explicitly observable in the simulation model. For example, can the analyst trace the influence of combat information on the management of forces by a given command echelon?

With the use of human gamers, the analyst can, at best, only indirectly observe the internal operations of the C^2 system. Questions involving the match between tactical decision processes and the technical support provided by the C^2 system can be addressed only through inference.

The use of computer science techniques for representing decision processes provides an explicit description of the C^2 processes. Consequently, the analyst is able to directly trace the effects of the C^2 system's technical support on C^2 functions.

Consistency

Consistency is defined as the ability of the model to produce repeatable and congruous behavior over a range of appropriate conditions. Consistency is essential to the comparison of simulation results produced during different executions of the model. In particular, the analyst must be assured that variations in model output are due to intended changes in model parameters and not because of unexplained deviations in the decision processes.

There is no guarantee of consistency when human gamers are used to represent the decision processes in a conflict simulation model. Changes in gaming personnel are likely to introduce noncontrollable deviations in model output through the influence of gamer personality and skill level. Even if there are no changes in gaming personnel, the analyst must contend with the possibility of learning effects. That is, the behavior of the gamers may vary over time as they become more familiar with the setting and operation of the simulation.

One technique used to provide consistency over a limited set of conditions involves the recording of gamer decisions. In certain simulation models, a standard set of tactical decisions made by the gamers may be repeatedly used in subsequent executions of the model. This technique is applicable only in situations where changes to other parameters and operations would not have normally resulted in different decision outcomes in each step of the simulation.

The use of computer science techniques provides a consistent framework for representing decision processes within a conflict simulation model. Behavior is completely specified by the model developer through mathematical expressions and formulations. If variable or stochastic behavior is desired, this can be produced through deliberate modifications to the appropriate production systems, signature tables, and so on.

Fidelity

Fidelity is defined as the extent to which the behavior of the simulation model matches the behavior of the real world. That is, the model should faithfully reproduce real world behavior over an appropriate range of conditions. The model should be robust in that it does not produce absurd results.

It would appear that the use of human gamers has an advantage over the use of computer science techniques in this regard. Quite simply, nothing represents a human decisionmaker as faithfully as a real person. Our limited knowledge of human decision processes and our limited ability to model different aspects of those processes suggests that fidelity is difficult to achieve with computer science techniques. Production systems, signature tables, and so on are the products of historical experience and problem understanding. New and unique problem circumstances may arise which do not fit existing conceptions. Hence, the user of such techniques must continually test to insure that the underlying conceptual foundations have not been violated by new conditions.

The use of human gamers, however, has its own set of fidelity problems. There are several factors which influence the ability of human gamers to faithfully represent combat decisionmakers. Among these factors are the level of tactical skill and experience possessed by the gamers, the motivation of the gamers, and the level of psychological stress provided in the gaming environment. In short, the analyst must take positive measures to achieve a reasonable level of fidelity with both approaches to representing decision processes.

Technical Risk

Technical risk is defined as the degree of difficulty likely to be encountered in developing a satisfactory simulation model. Given that a particular approach is selected for representing decision processes, what is the likelihood of producing a useable model?

The use of human gamers to represent decision processes entails little risk in the initial development of a conflict simulation model. With this approach, the model developer does not have to be concerned about the internal details of the decision processes. However, the model developer may later be faced with problems of scope, resolution, transparency, or consistency, depending upon the intended use of the model. Thus, some risk may be involved with achieving a model which completely satisfies the analyst's needs.

On the other hand, the use of computer science techniques to represent decision processes entails risk from the start. The development of robust decision models depends upon a comprehensive understanding of the problem domains and decision processes involved. Our limited knowledge of decision processes in semantically rich problem domains makes this task arduous for most tactical situations. Indeed, one does not even know the extent to which decision processes can be modeled. Thus, the risk involved with producing a satisfactory model is more directly visible, if not greater, with this approach to representing decision processes.

Observations and Considerations for the Future

As summarized in Figure 7, each approach to simulating tactical decision processes offers the analyst relative advantages. The use of human gamers in conflict simulation models offers greater potential for fidelity and incurs only moderate risk. The use of computer science techniques provides the analyst with greater potential for increased model scope, resolution, transparency and consistency.

It would seem attractive, therefore, to seek ways in which these different advantages could be exploited to serve the needs of the analyst. Accordingly, the remainder of the paper provides some thoughts on how both modeling approaches could be combined into an experimental testbed facility for the study of the human component in tactical C^2 systems.

Returning for a moment to the cognitive research discussed earlier, it can be observed that several interesting theories have emerged to guide our understanding of tactical decision processes in C^2 systems. For example, the work of Keen and Scott Morton suggests that it is important for the analyst to understand various aspects of decisionmaking, not all of which fit the rational man image. Results of other research imply the existence of different types of cognitive processes, only one of which fits the analytical definition. Still additional research has begun to explore the complexities of semantically rich problem domains and the behavior of man in dealing with those domains.

A major premise held by the author is that the simulation model developer can both exploit and assist the type of cognitive research just cited. The model developer can exploit this research by using its theories and findings to build a more robust conceptual framework for modeling and studying the human aspect in C^2. The model developer can assist cognitive science by providing a convenient and realistic environment for applied research.

One approach to linking the simulation model with cognitive research is the development of an experimental C^2 testbed. The essential features of this testbed include a basic conflict simulation model, gaming facilities, and a flexible software language for developing decision models.

The conflict simulation model would provide a realistic problem domain for the tactical C^2 system, much the same as provided with TALON or TAC ASSESSOR. The conflict simulation model would perform the general combat accounting functions necessary to keep track of logistics, movement, and attrition aspects of the air and ground operations. An air and ground C^2 structure would overlay this conflict model; however, the internal operations of each C^2 element would not be rigidly specified. In fact, each C^2 element would be designed to accept either human gamers or computer science models for representing its internal functions.

By providing generic C^2 elements, the C^2 testbed offers the opportunity to use human gamers and computer science techniques in an iterative fashion. Human gamers could be used to initially investigate the functions of a specific C^2 element. As more is learned about the decision processes and heuristics involved, analysts could construct realistic decision models for the C^2 element. Subsequent simulation exercises would then rely on the computer science models to represent the C^2 element. A return to the use of human gamers would occur when the decision models failed to provide robust behavior (under new combat conditions) or when the analyst desired to study the C^2 element in more depth.

The iterative use of human gamers and computer science techniques would systematically evolve a greater understanding of the decision processes involved in each C^2 element. Requirements for gaming facilities and personnel would be kept to a minimum by focusing their use in only one or two C^2 elements at a time. The richness and fidelity of a distributed decision system would be obtained by allowing the human gamers to interact with the decision models provided for other C^2 elements in the simulation model.

After several months of operation, it is anticipated that many of the lower echelon C^2 elements would be represented by fairly robust decision models. The degree of structure associated with many of the lower echelon decision processes would facilitate this development. The use of human gamers would tend to predominate at the higher echelon C^2 elements since these decision processes are less structured.

If properly constructed, the C^2 testbed would meet a variety of requirements for both operational and analytic communities. For the operational community, the C^2 testbed would provide a realistic setting for tactical battlestaff training and a flexible tool for defining detailed operational requirements. For the analytic community, the C^2 testbed would provide a research vehicle for investigating C^2 functions and a high fidelity model for evaluating new concepts, procedures, and hardware.

Above all, the C^2 testbed would provide an excellent communication media between the operational and analytic communities. The conflict simulation model would provide a common language and conceptual setting for discussing C^2 issues and exchanging ideas. This potential opportunity for improved communication between operator and analyst would be unique and hard to duplicate in any other setting.

A Final Word

Advances in cognitive science and simulation modeling offer great potential for systematically increasing our understanding of the human component of C^2. This, in turn, offers improved tools for discussing, analyzing, and defining the utility of C^2 systems to tactical combat forces.

Progress will not be achieved easily, or by accident. Knowledge from several disciplines must be organized, synthesized, and integrated in a program of applied research. This crossing of discipline/experience boundaries has not always been an easy task for many analysts. Accordingly, success in this endeavor will depend as much on philosophical commitment to the research as on a financial commitment.

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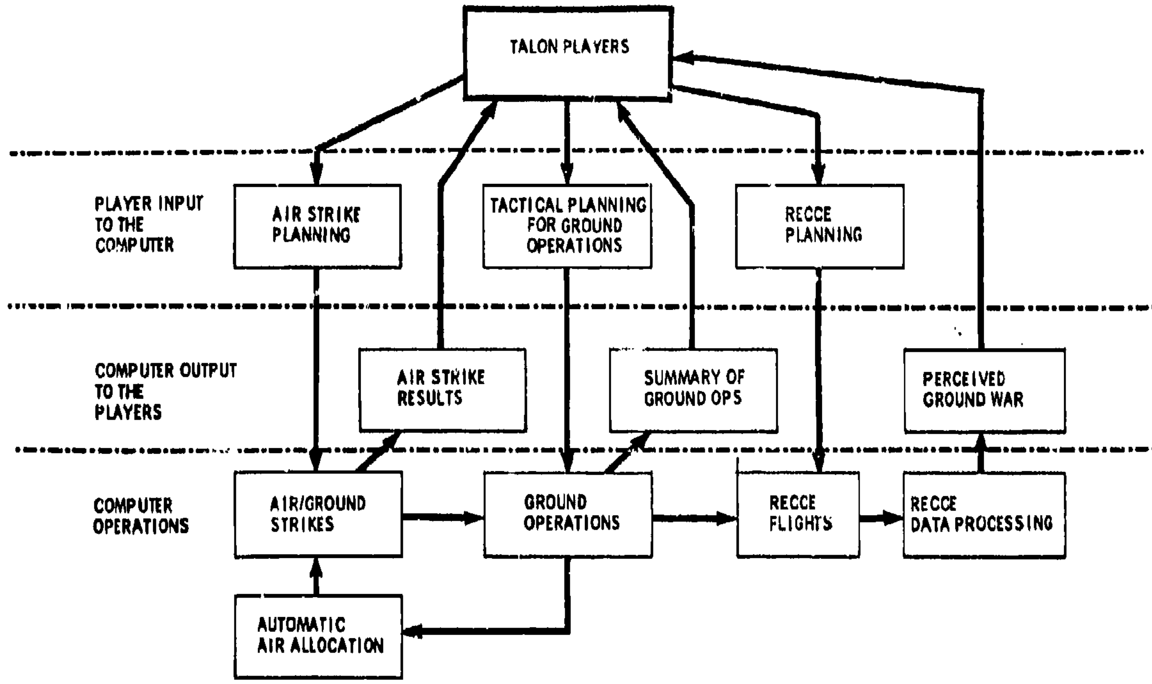


Fig.1 Gamer interactions with TALON

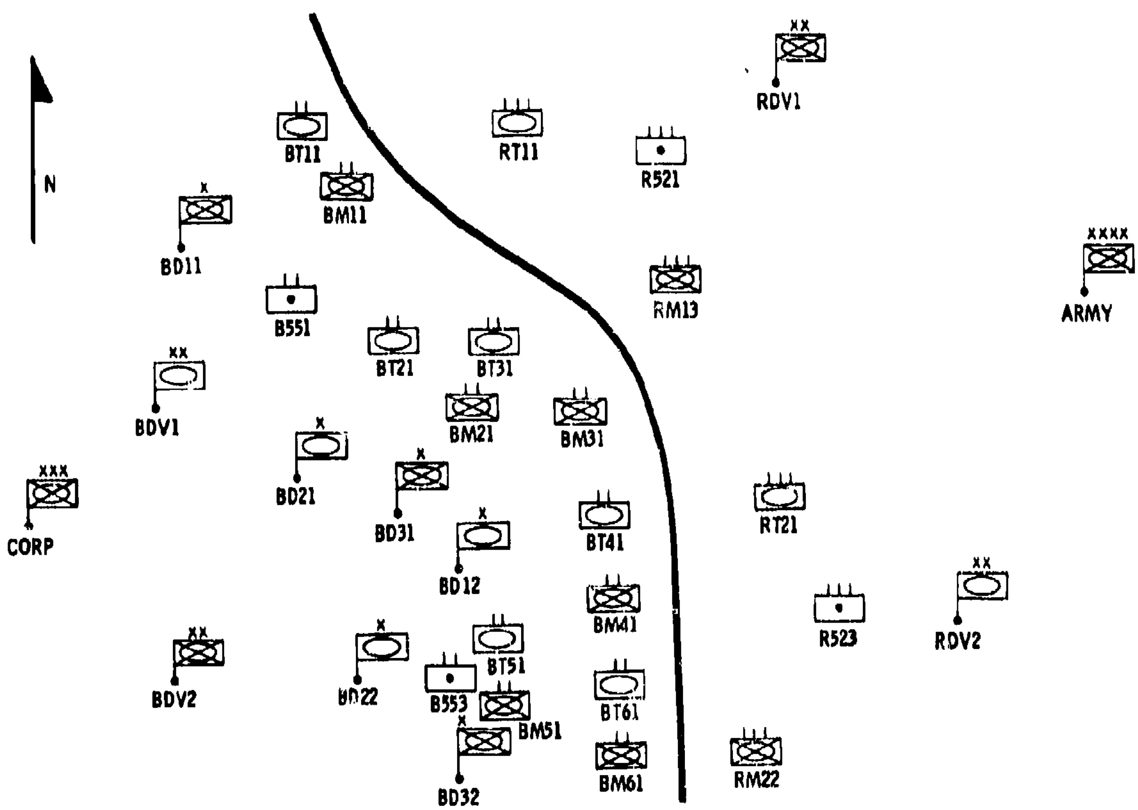


Fig.2 Ground unit C² structure in TAC assessor

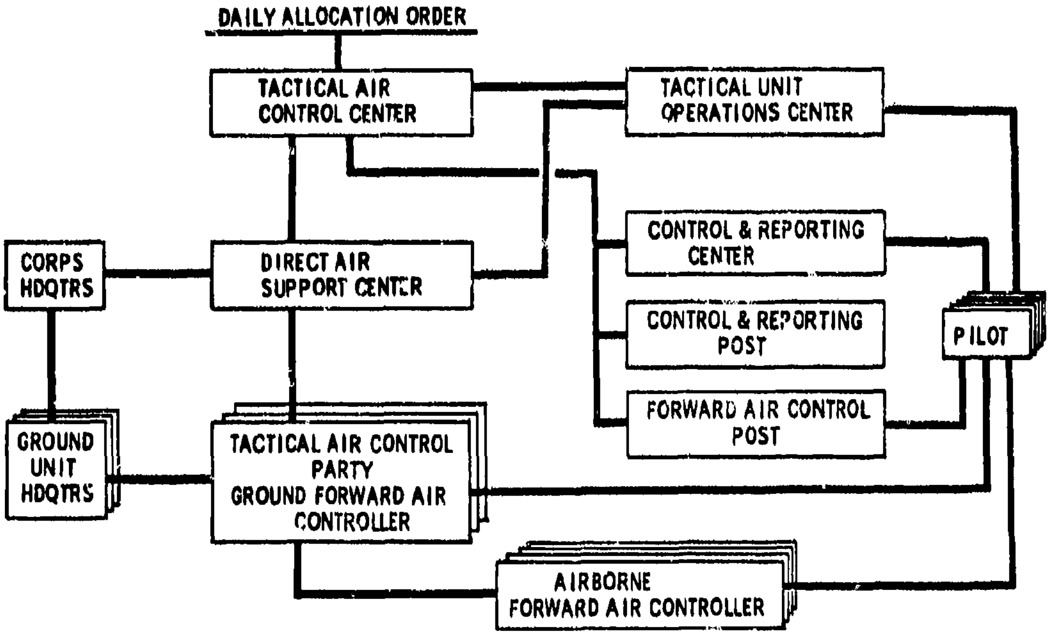


Fig.3 Air C² structure in TAC assessor

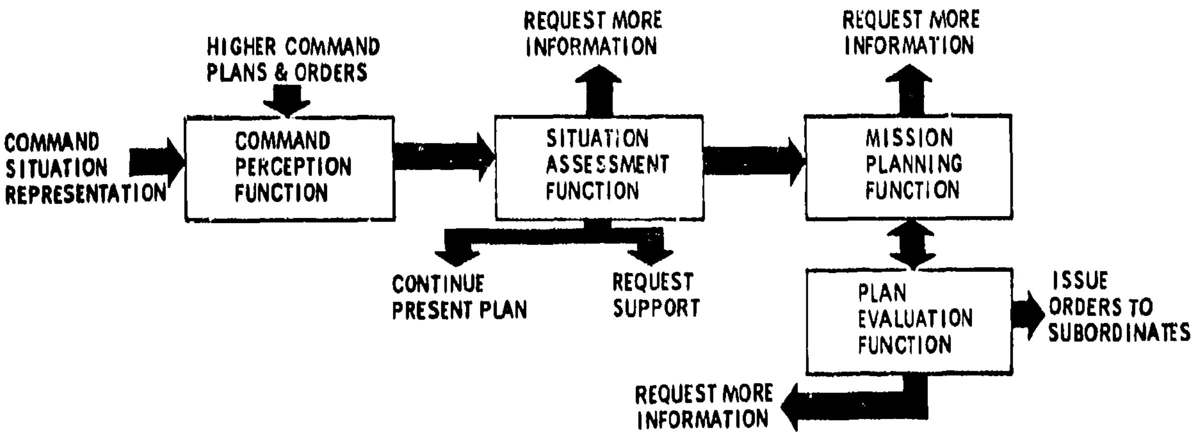


Fig.4 Generic ground unit headquarters' functions

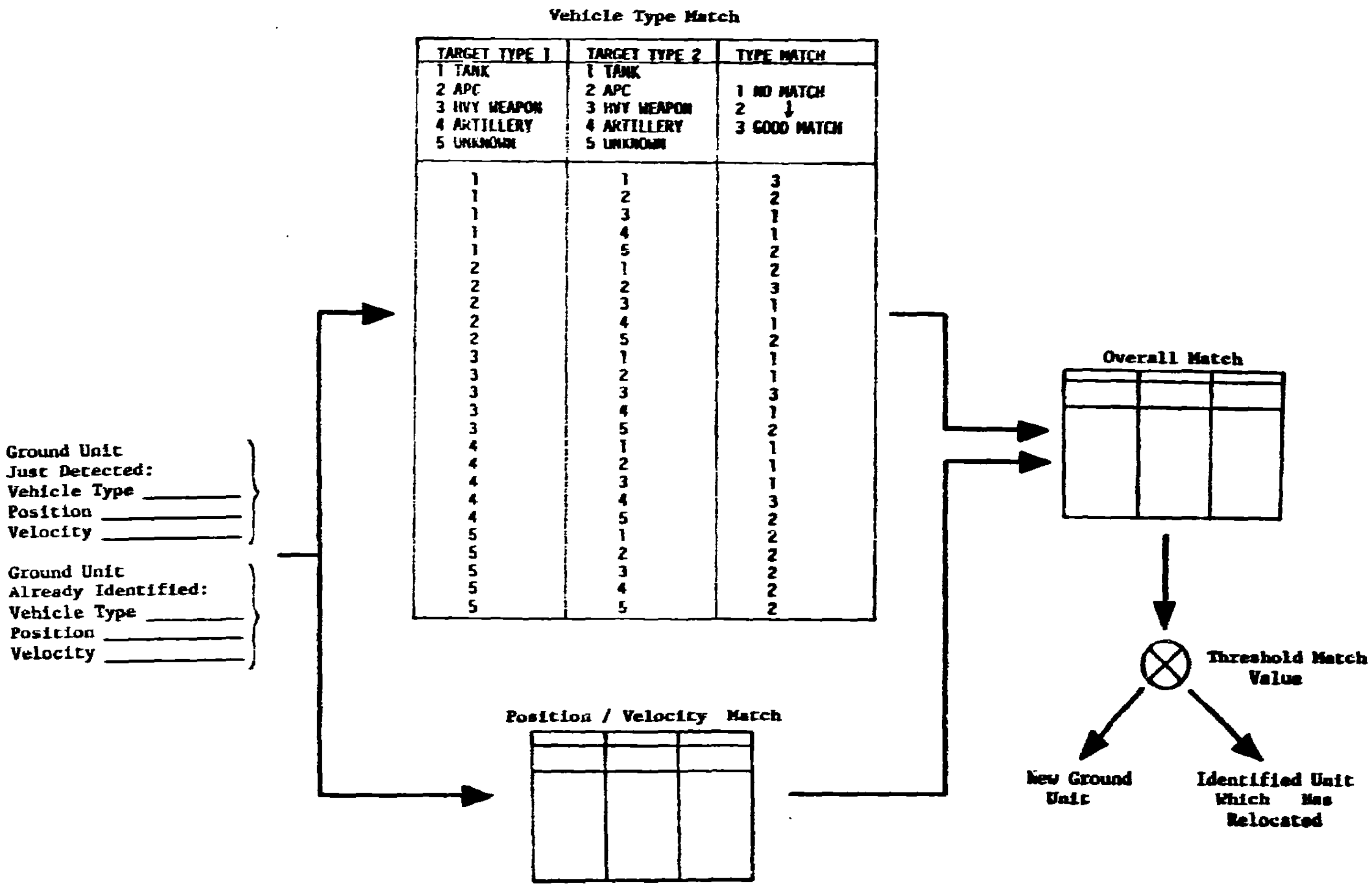
COMMANDER'S HEURISTIC SET FOR COMBAT UNIT MISSION ASSIGNMENT:

- IF THE MISSION OF THE UNIT IS TO ATTACK, THEN
  - THE FRONT LINE UNIT STRENGTH SHOULD BE 150% OF THE EXPECTED ENEMY STRENGTH
  - ASSUME THAT THE ENEMY CAN BRING 80% OF HIS STRENGTH TO BEAR.
- IF THE MISSION OF THE UNIT IS TO DEFEND, THEN
  - THE FRONT LINE UNIT STRENGTH SHOULD BE 120% OF THE EXPECTED ENEMY STRENGTH
  - ASSUME THAT THE ENEMY CAN BRING 60% OF HIS STRENGTH TO BEAR.
- ASSIGN ALL ARTILLERY UNITS AS SUPPORT UNITS.
- ASSIGN ENOUGH REMAINING COMBAT UNITS AS FRONT LINE UNITS TO ACHIEVE THE DESIRED FRONT LINE STRENGTH RATIO. SELECT THESE UNITS ON THE BASIS OF THEIR PROXIMITY TO THE ENEMY UNITS LOCATION.
- ASSIGN ALL REMAINING UNITS AS RESERVE UNITS.

CORRESPONDING PRODUCTION SYSTEM:

```
$R1$ .IF. HQ MISSION .IS. H(ATTK) .DO. SET (WINNING FACTOR, 1.5) .AND.
                                      SET (ENEMY STRENGTH DISTRIBUTION, 0.80)
$R2$ .IF. HQ MISSION .IS. H(DFND) .DO. SET (WINNING FACTOR, 1.2) .AND.
                                      SET (ENEMY STRENGTH DISTRIBUTION, 0.60)
$R3$ .DO. FLU STRENGTH = EXPECTED ENEMY STRENGTH * WINNING FACTOR *
                         ENEMY STRENGTH DISTRIBUTION
$R4$ .FA. UNITS .IF. TYPE (UNITS) .IS. H(ARTY)
                .DO. DECREASE (FLU STRENGTH, STRENGTH (UNITS)) .AND.
                     MAKE SUPPORT (UNITS)
$R5$ .DO. SET (SORTED UNITS, ORDERED ON DISTANCE (UNITS, ENEMY REF PT))
$R6$ .FA. SORTED UNITS .IF. FLU STRENGTH .GE. 0.0 .AND
                         ROLE (SORTED UNITS) .IS NOT. H (SPRT)
     .DO. DECREASE (FLU STRENGTH, STRENGTH (SORTED UNITS)) .AND.
          MAKE FRONT LINE (SORTED UNITS)
$R7$ .FA. UNITS .IF. ROLE (UNITS) .IS NOT. H (SPRT) .AND.
                     ROLE (UNITS) .IS NOT. H (FLU)
                .DO. MAKE RESERVE (UNITS)
```

Fig.5 Heuristic set and corresponding production system



TARGET TYPE 1 1 TANK 2 APC 3 HVY WEAPON 4 ARTILLERY 5 UNKNOWN	TARGET TYPE 2 1 TANK 2 APC 3 HVY WEAPON 4 ARTILLERY 5 UNKNOWN	TYPE MATCH 1 NO MATCH 2 ↓ 3 GOOD MATCH
1	1	3
1	2	2
1	3	1
1	4	1
1	5	2
2	1	2
2	2	3
2	3	1
2	4	1
2	5	2
3	1	1
3	2	1
3	3	3
3	4	1
3	5	2
4	1	1
4	2	1
4	3	1
4	4	3
4	5	2
5	1	2
5	2	2
5	3	2
5	4	2
5	5	2

Fig.6 Use of signature tables for updating battlefield perception

SIMULATION APPROACH TO REPRESENTING THE C^2 SYSTEM	HUMAN GAMERS	COMPUTER SCIENCE TECHNIQUES
SCOPE & RESOLUTION	AVAILABILITY OF FACILITY AND PERSONNEL RESOURCES LIMITS THE NUMBER OF INDIVIDUAL C^2 ELEMENTS PORTRAYED	NO LIMIT TO THE NUMBER OF C^2 ELEMENTS PORTRAYED, PROVIDED THAT THEY CAN BE MODELED
TRANSPARENCY	INTERNAL OPERATIONS OF THE C^2 SYSTEM CAN BE ADDRESSED ONLY THROUGH INFERENCE	MATHEMATICAL DESCRIPTIONS OF THE DECISION PROCESSES PROVIDE EXPLICIT VISIBILITY OF THE C^2 FUNCTIONS
CONSISTENCY	CHANGES IN GAMING PERSONNEL AND LEARNING EFFECTS CAN INTRODUCE NONCONTROLLED DEVIATIONS IN C^2 SYSTEM BEHAVIOR	CONSISTENCY OF THE C^2 SYSTEM BEHAVIOR IS DIRECTLY CONTROLLED BY THE MODEL DEVELOPER
FIDELITY	HUMAN GAMERS PROVIDE THE GREATEST POTENTIAL FOR FIDELITY, SUBJECT TO SKILL AND KNOWLEDGE LEVELS, MOTIVATION, AND STRESS	CONTINUAL TESTING IS REQUIRED TO INSURE THAT MODEL DOES NOT PRODUCE ABSURD BEHAVIOR UNDER NEW CONDITIONS
TECHNICAL RISK	SOME RISK INVOLVED WITH ACHIEVING DESIRED LEVELS OF SCOPE, RESOLUTION, TRANSPARENCY, AND CONSISTENCY	DIFFICULTIES IN UNDERSTANDING PROBLEM DOMAIN AND DECISION PROCESSES REPRESENT A HIGHLY VISIBLE RISK

Fig.7 Relative comparison of simulation approaches

VERIFICATION AND VALIDATION OF AVIONIC SIMULATIONS

Sabina H. Saib
General Research Corporation
5383 Hollister Avenue
PO Box 6770
Santa Barbara, California 93111

SUMMARY

Avionic simulations require verification and validation so that the simulation results can be applied reliably to actual avionic systems. This paper discusses software design methods as well as currently available automated aids for verification and validation. Reverification and revalidation of a simulation after changes are made will be presented.

Simulations can be designed for ease of verification and validation. Guidelines will be presented to show how simulation software can be developed with verification in mind. The most powerful techniques require additional statements known as assertions. The assertions can then be used to check the validity of the simulation.

Some automated verification and validation tools are available today. The appliability of these tools to avionic simulations will be discussed. The future directions that are seen for such tools will be presented.

Finally the reasons for change control will be presented, and a solution to the problem will be proposed. Since most effort in a simulation is devoted to changes for improvement in the system, it is important to verify what the changes affect. Techniques which automatically detect possible side effects due to a change will be discussed.

1. INTRODUCTION

Digital simulations of avionic systems are being used and will continue to be used to test new concepts and to subject systems to test environments which are costly or impractical to actually use. The necessity for digital simulations has required acceptance of simulation results which are produced under conditions where previous practical experience gives little or no guidance. As a consequence, simulation results have been accepted as correct when indeed they are erroneous. A recent well publicized error in a simulation of earthquake stresses caused the shutdown of five nuclear power plants in the U.S. It is conceivable that a similar error in an avionic simulation could result in a loss of certification for aircraft or avionics equipment.

Simulations are subject to many sources of error. Errors can be made in the assumptions made in deriving the models, in the hardware on which the simulation operates, in the data provided to the simulation, and in the interpretation of the results. This paper is concerned with another source of error, one that is of serious concern - errors in the digital simulation software.

These errors are removed in a process called verification and validation. The most common techniques currently used in verification and validation are based on exercising the complete simulation through a large variety of test conditions. The tests, while comprehensive, depend on the ingenuity of the testers to detect the errors present in the entire system. While the use of the complete system is necessary to obtain measures of system performance, there are certain problems in using this approach to perform verification and validation. The primary problems are:

1. The verification and validation tests are not repeatable. Another group of individuals may perform a different set of tests or the same group at a different time may choose another set of tools.

2. The verification and validation tests are performed late in the life cycle of the project. This results in costs not only to fix the error but in costs due to the additional delay in the project and due to the need for retesting what had been tested before. Errors are corrected under pressure and side effects due to the changes are not well understood.

3. The verification and validation tests do not provide a quantitative measure of the goodness of the test. They are often designed to find errors but not to yield a measure of correctness.

4. Experience has indicated that errors are found in simulations even after they have been thoroughly verified and validated.

There is no one single answer or a complete solution to this set of problems. However there is a set of approaches, techniques, and tools which can help alleviate the problems as they exist today. We expect these will be improved as more experience and data is gathered on the use of the currently available solutions.

2. DESIGN ASPECTS

A trained electronics engineer can examine a radio, a television, a radar, or a guidance system and in a very short time give a judgement on how easy it is to test, to change, or to maintain compared to another design of the same system. Any engineer will agree that the ability to test the system is based on the original design and results from early design decisions.

It has not been until recently that it was recognized that software verification and validation is also dependent on design decisions and that a design from one source can be far easier to test for correctness than another design that claims to perform the same function.

Achieving simulation software which is easier to verify and to validate than the average simulation can be done by imposing restrictions during preparation of the simulation software. Some of the restrictions require management review for their enforcement. Others can be imposed by automated techniques which produce reports on compliance.

An example of such a restriction, is the requirement that meaningful names be used such as TIME, SPEED, HEIGHT instead of names such as X1, X2, X3. We would not expect a test pilot to be faced with examining instruments which are not clearly labeled. Likewise we should not expect a tester to examine a software simulation with abstract names.

A nice feature of using meaningful names is that very little computer knowledge is required to impose this restriction. A manager can pick up any simulation, ask a programmer to point to all the variable names, and give a rapid opinion as to whether the design contains meaningful names.

While no known current software analysis tool yields this judgement, one could envision a tool which looks up all variable names in a dictionary such as is used in current spelling checkers and yields an index of the number of names found versus the total number of names as well as a list of names which were not found.

An excuse which is often given for the use of meaningless names is that the programming language restricts names to 6 characters or less. The use of such languages should be restricted to non-critical simulations. They severely impact the ability of anyone to verify and to validate the software although cross reference lists to meaningful names can help alleviate the problem.

Every variable used in a digital simulation has a finite range. In the days of analog simulation it was a challenge to scale the range of each varible to the linear ranges of the analog devices. At least then checks were made on the actual ranges of the variables and the variables were clamped to maximum or minimum values. Often the only check made in current simulations is when the variable overflows or underflows a computer register. When the correct range of variables is required to be specified in a design, this knowledge can be used by a tester to generate checks and to generate reasonable test data.

A good design requires the use of a specification which gives the maximum and minimum possible values for each variable to check that all inputs and all outputs from each part of the simulation are within the specified units.

Every design engineer is taught to use dimensional analysis to verify that correct units are used in equations and in conversions. This powerful technique is not used in software testing of simulations. While a manual analysis is possible, it can be tedious. Automated dimensional analysis is practical and has been implemented in at least one test tool. It requires that the designer specify the units of each variable such as:

```
VELOCITY: REAL UNITS METER/SECOND;
TIME: REAL UNITS SECOND;
DISTANCE: REAL UNITS MILE;
METERS_TO_MILE: REAL UNITS METER/MILE;
```

Then a equation used in a simulation such as:

```
DISTANCE:=VELOCITY*TIME*METERS_TO_MILE;
```

$$\text{MILE} \quad \overset{?}{=} \frac{\text{METER}}{\text{SECOND}} \times \text{SECOND} \times \frac{\text{METER}}{\text{MILE}}$$

can be checked to determine that the units of distance are inconsistent with the units of velocity times time times the conversion constant.

In a simulation, software designers are faced with at least two different types of arithmetic in the computer program. The decision of which type of arithmetic to appropriate is a decision that should be made be the designer. An example of what not to do in a simulation is the following:

$$\int_0^{10} x^2 dt$$

An integration procedure based on

$$\sum_0^{10} x^2 \Delta x \text{ where } \Delta x = 0.1$$

will result in a significant error if the implementor uses steps of 0.1 to decide when to terminate the sum instead of counting the number of steps.

Names are used to represent functions, variables, and constants in a simulation. If the use of each name is known to a verifier, it can aid the testing process. For example, if it is known that a name represents a constant, automatic checks are possible to determine that nowhere in the design is that name assigned another value. If the order of each function is specified, automatic checks on the correct order of invocation can be performed. In addition checks on whether the variables and constants for a function are used as inputs, outputs or as local variables can be made. This use of names should be specified in a design so the tester or test tool can check whether the implemented program satisifes the design.

In a design, it is a common practice to use the same name such as X, Y, or Z to denote different quantities. For example, Z may at one time be the altitude above ground level and at another time be the difference in altitudes between two aircraft. It is far better to use names such as:

HEIGHT_ABOVE_GROUND and DELTA_ALTITUDE

Separation of inputs and outputs in a design allows for easier testing. The common practice of using the same name for inputs and outputs means that the program has a feed back loop as shown in Fig. 1.

When inputs are separated from outputs, stronger tests can be applied; and fault tolerance techniques which depend on restoring input values are made simpler. One of the strong tests is that inputs are not altered and that outputs are altered only at interfaces. When the inputs and outputs are the same, a tester cannot derive the response of the system.

An aid to a tester which can also be used in a formal design review to aid communication between system designers and implementors is a natural language presentation of the formal design. Ideally the natural language phrases come from the requirements for the design. These phrases are combined with the key words of the programming language to document the design of the program. The keywords show the control structure and the natural language shows the processing and decisions that are performed.

An example of such a description is:

<u>IF</u> the aircraft altitude is less than 100 meters
  turn on the ground proximity buzzer
<u>END IF</u>

The keywords <u>IF</u> and <u>END IF</u> point out that a decision is to be made. The natural language phrases describe the decision and subsequent processing in terms that are more easily understood than the program that will be implemented. Logic errors can be caught more easily with this type of description than a pure natural language description.

Design checks against a requirements document generally are done via manual analysis.

3. IMPLEMENTATION ASPECTS

It is far easier to verify a small simulation than a large simulation. The number of problems that must be corrected appears to be an exponential function of simulation size. Although it is not well understood exactly why breaking a simulation into small parts helps the size problem, it is known that a restriction on the size of each part or module of the simulation simplifies the verification and validation of the program.

A reasonable restriction on the module size appears to be the number of lines that can be displayed on the face of a scope or printed on a page. When this restriction is imposed, the verification and validation of each module is simplified. Each module can be tested for a large set of testcases. While a large simulation cannot be tested for all possible combinations of paths or values, it may be feasible to at least exercise each module individually through each path and for most input values.

Verification and validation is also aided by the use of simple control structures instead of complex control structures. It has been shown that only three kinds of control structures are necessary to write any computer program, that less time is required to write, to test, and to maintain a program using simple control structures and the use of such techniques is considered a substitute for flowcharts. However, in the absence of an automated tool to test whether structured control constructs have been used, a visual inspection of the flowcharts can verify that the simulation structure is correct such as shown in Fig. 2.

Even a small module can contain an unnecessary number of paths. Each unnecessary test adds greatly to the testing effort since complete testing is proportional to 2^N where N is the number of decision points. Reorganization of the implementation can often reduce the number of decisions.

Data structures can dramatically affect the algorithm that is needed to operate on the data. Algorithms exist which can reduce the complexity and efficiency of a simulation. Since an efficiant algorithm allows more test cases to be used, the various data strucures available for data representation should be traded off during implementation. The trade off should consider program size, number of decisions, and execution time. These all effect the verification of the program.

On the other hand, while data structures are powerful simplifiers in a program they introduce potential sources of error for a verifier. The data structures must be protected from illegal access. The best way found to provide this protection is define a small library of well tested functions which can test for correct accesses as well as provide access. Access to data structures should be by single integer variables or constants, never by expressions.

Particular attention should be paid to loop structure. The best type of loop is one which computes a fixed number of iterations. If this is done, infinite loops are prevented. Within loops, it is best to have as few decisions as possible since loops have the effect of multiplying the number of paths in the program.

Thus it is best for verification purposes to iterate a series expression 100 times instead of iterating it a variable number of times based on the truncation error. Also loops should count using integer arithmetic instead of floating point arithmetic to avoid erroneous counts based on approximate arithmentic.

A good practice for all programs is to declare all variables, and the types of all variables. A method or tool should check that all variables are used and that the types are not mixed in expressions, across

modules, or across statements. These practices known as strong typing prevent unexpected errors due to data type conversions or incorrect data representation. Tools exist which can check that these kinds of errors are not present.

A significant problem area in simulations is the part that performs input and output. Although not a solution to the problem, isolation of the places that perform input and output to a small number aids verification and validation. It allows this potential problem area to be tested separately and if the machine, language dialect, or operating system is changed, the modules which will be most affected will be known. Tools presently exist which pinpoint where input and output are performed.

Missing initializations are a common source of error. Explicit initialization of all variables known throughout the simulation should be performed in a special module. Variables known in just one module should be initialized by that module. Tools are available to perform this checking, but explicit initialization at designated points is superior for understanding by the tester.

4. AUTOMATED AIDS

Automated aids are available to automatically provide verification and validation for programs written in several of the common programming languages: FORTRAN, JOVIAL, and PASCAL. Future aids will be developed for COBOL and ADA. Tools that are currently available can provide for static analysis, dynamic analysis, and configuration control of very large simulations.

Static analysis is provided in automated aids to check for common programming errors without requiring program execution. In a language such as FORTRAN which performs few checks on data types and modules, static analysis is extremely valuable in detecting errors which compilers do not locate. Even in a language such as PASCAL or ADA, many of the verification tests are useful.

An example of a static analysis technique which is useful in any of the current languages is set/use analysis. This analysis ensures that all variables are set before use and that all variables are used after being set. Set/use analysis detects uninitialized variables, dead variables, and mispelled variables. A very large number of errors can be detected by this technique. From 15-25% of all semantic errors are due to this simple misusage of variables, especially in programs which use a large global database.

Another static analysis technique which can be applied to simulations written in any of the common high level languages is loop analysis. Loop analysis can detect certain classes of infinite loops. This analysis uses a combination of graph analysis, data flow analysis, and symbolic execution to locate conditions which will cause improper loop termination.

An example of improper loop termination is when a program does not alter the loop control variable on all paths. Data flow analysis of loop control variables over all paths in a loop can check automatically for loop variable alteration.

Another example of improper loop termination is an incorrect loop predicate which will cause the loop to loop forever.

```
WHILE I>N DO
   FLIGHT [I]:=DESTINATION [I];
   I:=I-1;
END WHILE;
```

By symbolically executing the loop control variable, I, on each path in the loop and using the loop predicate I>N it can be shown that this loop will never terminate since $I-1 \not> I$. This automatic analysis can be performed currently for loop variables which are altered monotonically.

Future loop analysis may also include tests on proper loop structure such as requiring:

control variable intialization before the loop
control variable alteration within the loop
tests on the control variable to exit the loop
and proper nesting of loops.

Mode analysis is useful in simulation languages which do not have compilers which perform strong typing. It is particularly valuable in FORTRAN since most FORTRAN compilers produce no warnings about mixed mode expressions. It is also valuable in checking for interface consistency between separately compiled programs.

Besides mode checking, interface consistency checks which are powerful are:

checks for the same number of parameters between formal and actual parameters

checks for the input/output consistency between the invoking program and the invoked program

checks for the physical units consistency between the formal and actual parameters

Interface consistency is one of the most common problem areas because different people often work on different parts of a simulation. By eliminating interface problems at an early stage through static analysis, the simulators can concentrate on the functional aspects of the program.

The functional aspects of a simulation must be verified and validated by dynamic testing. However there are tools which can aid this testing. These tools are designed to complement the normal test environment by automatically adding probes to the program.

The most common aid to testing is the path test analyzer. This type of test tool puts probes in a program at decision points. Then when the program is executed, the probes collect data when the path is executed. After execution, the test file is available to analyze what parts of the program was executed, how much time was spent in each part, and how many test cases were run. This can be done whether the program terminates normally or not. It provides management with information as to how throughly a simulation has been tested.

Future path test analyzers will provide information which will be used to give a quantitative estimate of simulation reliability. This will require analysis of currently collected data to determine the number of paths tested out of the total number of possible paths and the number of data values tested out of the total number of possible data values.

Another aid to dynamic testing is the assertion analyzer. Assertions or checks which have been placed in a simulation such as

ASSERT HEIGHT > MINIMUM ALTITUDE;

can be instrumented so that assertion violations cause the automatic generation of error messages. In the future, such assertions may be used for automatic test data generation for large numbers of test cases to better validate programs.

In any simulation, changes are constantly being made. Any practical software tool must be able to check changes to a program without requiring reanalysis of the entire program. In addition, the aid should also be able to detect the parts of the program that are affected by the change and report on the parts that need retesting.

One approach to this problem stores a description of the interface of each part of the program. The interface includes the parameters, global variables, and assertions on these variables. Any time a part of the program is changed, a new interface description for that part is created. The new interface is checked for consistency with the internal source of the changed part and with the other interfaces in the system.

5. CONCLUSION

The verification and validation of avionics simulations starts with the design of the simulation. Standards for design and implementation can aid automated analysis and eliminate common errors at an early date. Tools are currently available to perform automated analysis and to assist program testing.

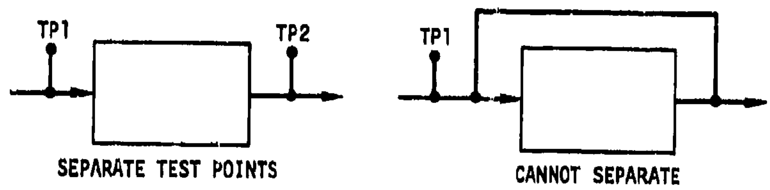


Figure 1. Separate Inputs and Outputs

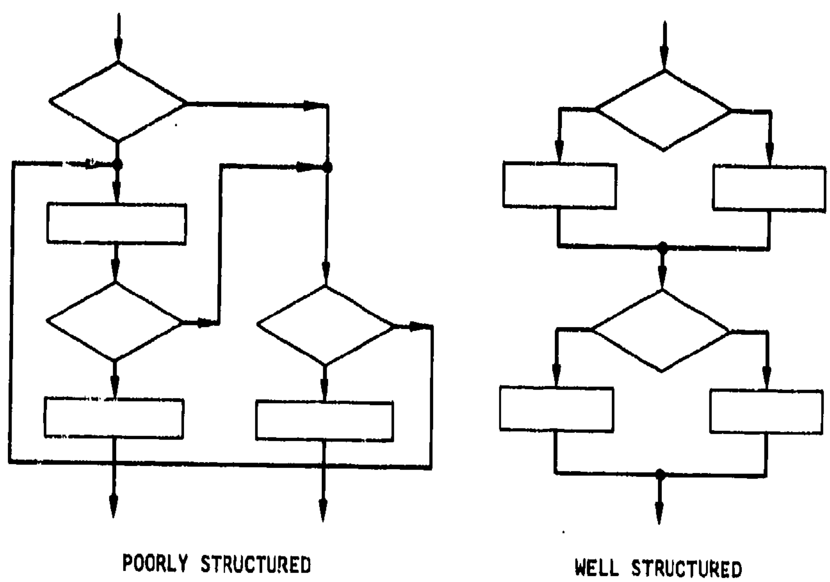


Figure 2. Flowchart Inspection

OBJECTIVES FOR BUILDING AN EXPERIMENTAL CCIS

Ingrid Hollinde

Forschungsinstitut für Funk und Mathematik
Werthhoven Konigstrasse 2
D 5307 Wachtberg

SUMMARY

Building ADP-supported Command and Control Informationsytems (CCIS) is a complex process which needs special development strategies. One of the aids in this process is an experimental CCIS, which helps the military commander to understand the possibilities of CCIS and which supports the dialogue between potential user and developer. One of these experimental CCIS is the system EMFIS, which was developed by the Forschungsinstitut für Funk und Mathematik in cooperation with the companies Bunker Ramo Corp. and Siemens. The system was developed from 1969 - 1974 and was lately used in WINTEX/CIMEX 79 to clarify the preconditions for the use of ADP-support in the C^2-process.

1. INTRODUCTION

In this paper I would like to

- state the problem of integrating CCIS into the C^2-process
- say some words about feasible strategies to develop CCIS
- derivate from the above the necessity of experimental CCIS and give a short description of the experimental system EMFIS developed by our institute
- describe experiences of preparation and performance of a test in exercise, i.e. use of EMFIS in WINTEX/CIMEX 79.

2. INTEGRATION OF CCIS

2.1 Man-Machine Interface

Let me start with the conclusions of a paper presented at the 22nd Commanders Conference of the Bundeswehr (Eberhard, H., 1978):

> "When the military commander wants to make effective use of technical means, he needs a high sense of responsibility to use all possibilities and not to exceed the limits. Therefore I have summarized the requirements, which derivate from my considerations in the order I have stated them.
>
> Of essential importance are:
>
> - the interface problems need special attention
> - the use of technical means must be reasonable and clear
> - training must lead to complete control by the military user and overstrain must be avoided
> - above all stands the education to be a responsible commander.

When all this is taken into consideration, knowing that a system cannot be more intelligent than it was preplanned, but that it can enlarge the human intelligence, then it is clear that the area of human decisions will be reserved for all determining decisions , all decisions dependent on situation and all improvisation.

Therefore I would like to complete the requirement, that the military commander should first be trained and educated to be a soldier by the addendum that the education to use and control the technical means cannot be separated from the military education."

This quotation states the main reasons for the use of experimental CCIS, in order to avoid malfunction in operational employment:

- to recognize and solve interface problems
- to demonstrate technical means and to rouse understanding
- to serve as a training system
- to prove how well technical means can be integrated into the C^2-process.

2.2 Steps of the C^2-process

It is advisable to investigate the C^2-process, where and how technical means like an ADP-supported CCIS may support this process (Fig. 1). There are various, but similar ways to group the C^2-Process by "steps" (Wust, H., 1974).

Some of these steps can be totally or mainly taken over by an ADP-supported CCIS, e.g. collecting and displaying information. Other steps can be supported by such a system like to analyse information, to propose measures, to issue orders. But some of these steps stay mainly or completely in the responsibility of the commander like evaluation and decision. The degree of automation will also highly depend on the mission which is supported. The more predictable the types of processes are, the higher the degree of automation will be.

3. PROBLEMS OF DEVELOPMENT

Besides the problem of integrating an ADP-supported CCIS into the C^2-process the problem focuses in the complex process of developing these systems.

3.1 Development Strategies

Several development strategies were created in course of time (Fig. 2) (Wagner, K.H. 1978). The first approach is the insular approach which solves singular problems, so that mostly clearcut projects can be defined, interdepencies will be neglected, difficulties in competence do not occur. The projects are manageable, analysis is done for this single project only, times of development are relatively short. But interoperability with other systems is normally lacking, integration of systems mostly impossible. Priorities are defined by elbows and not for the total organisation.

The contrary approach is the total systems approach which may have the goal of one centralized information system or a distributed system. This approach tries to avoid the disadvantages of the insular approach, for the planned system should be optimized over the total organisation and should guarantee integration. However, this approach shows other disadvantages like requiring a detailed analysis of the whole organisation which either has to be done with an enormous effort of personnel and coordination, or will become a never ending task, while the living organisation is changing, so that the analysis might be outdated before the project is finished.

The aligned insular approach tries to find compromises. The approach needs a general concept which considers the financial and organisational possibilities and states priorities. This concept is based upon analysis of organisation and missions. Within this framework surveyable projects can be defined at focal points of special need and/or ADP-characteristics. The interoperability is not guaranteed per se, but can be controlled by the management which also has to direct this aligned approach. This leads to the essential problem of this approach, for it needs a capable management, which controls the single projects, solves the interface problems and guarantees interoperability throughout all competences. Without this management the approach will degenerate to the former insular approach with all its disadvantages.

3.2 Systemconcepts for CCIS

Sometimes you find the opinion that integration- and development problems can be reduced by acquisition of a proved system (Fig. 3). But they should consider that systems are supposed to support special missions and fit into existing organisations. When mission and organisation are identical or at least strongly similar this way is feasible, but in most of the cases these conditions cannot be fulfilled. Considering the fact that mission and organisation define the requirements on which the system concept is based, then it becomes obvious how questionable this way might be. Does this mean now that for any mission and/or any organisation own ADP-supported information systems have to be developed or is it feasible to find compromises?

When the analysis of mission and organisation of A and B shows a high commonality then it is feasible to enlarge system A in order to cover the requirements of B. That is especially possible when the system structure is modular.

A further result of analysis may be that mission and/or organisation differ quite a lot, but that certain functions show common features, e.g. message handling or graphical situation monitoring. When these functions can be separated then dedicated systems can be developed for common use.
If neither total system concept nor the dedicated one is feasible or reasonable, then it will be necessary that a system A and a system B will be developed. But in order to come to interoperable systems, a strong control function has to observe and control the single projects and especially the interfaces.

The most favourable system concept in our opinion is a combination of dedicated and interoperable systems. Assumed the analysis shows that the requirements have special systemfunctions in common like message handling, graphical display, event monitoring, data storage, dialog functions and security handling. Then it might be feasible to develop a common operating system enlarged by these systemfunctions which can form the nucleus for the individual but interoperable sytems for A and B.

3.3 Development Phases.

Normally there is no discussion about the sequence of development phases, even when they are named differently. I will use here the officially determined phases of the German MoD (BMVg/Sts/Org, 1973).

These are the phases

- Preliminary Phase
- Concept Phase
- Definition Phase
- Development Phase
- Introduction and Operation Phase.

The figure shows a linear sequence which is feasible for simple projects. Normally the development of ADP-supported CCIS is not simple, but rather complex, which makes feed-backs unavoidable.

Here the experimental system will be involved, which should not only support the process of integration, but the development process as well.

In the preliminary phase experimental systems may serve to gain the understanding and motivation of the potential user and to make feasibility studies. Before the final system goes into operation the experimental system will serve as a training system and for test of the necessary procedural and organisational rules.

When a modular extension of the operational system is planned, experiments will support the integration of new modules without disturbing operation.

Let me summarize the reasons for using experimental systems:
- they accompany the development phases
- they serve to clarify the organisational and procedural preconditions for the use of CCIS
- they serve as training systems for the future users
- they allow system comparisons and feasibility investigations
- in an interim phase they may become operational on selected areas.

4. DESCRIPTION OF THE EMFIS-SYSTEM

I would like to present now an example of an experimental system.
EMFIS is supposed to serve as an experimental Command and Control Information System for the Supreme Command Bundeswehr. It was developed by the Forschungsinstitut für Funk und Mathematik in cooperation with the companies Bunker Ramo Corp. and Siemens.

EMFIS consists of a system part which is user-independent, except that it was structured to serve in static HQs, and of a user-oriented application model, of which several versions for different user groups are existing.

4.1 EMFIS Systemfunctions

The essential systemfunctions in EMFIS are:
- the actual gathering and updating of data
- the relatively easy connexion of files by predefined transactions started by the user
- the dialogue between user and system, mainly in parametrized form, with formats to be filled in. This makes it possible to have an extensive check for errors and inconsistencies, to prevent an incorrectness of the actual data base. The parametrized dialogue also supports the user in formulating the updating reports as well as the queries
- the multiple access allows to read and/or write at the same data base from different terminals. This makes it necessary to control transactions for possible conflicts
- the data base recovery by back-up and restart routines as well as system readiness under reduced conditions
- access control which meets the special security regulations for handling classified material in the military area, in a way which still allows the necessary flexibility
- display of information in alphanumeric form, e.g. in tabular form and in graphical form as charts, diagrams and situation maps.

4.2 EMFIS application model

The main application model in EMFIS has the objective to show the combat readiness of own forces focusing on crisis and tension. The combat readiness of own forces will be mainly represented by the status of alert, mobilisation, personnel, logistics and deployment. This will cover the information requirements of the Supreme Command Bundeswehr only partially, but represents an essential model in the sense of the experiment.

5. EMFIS-TEST in WINTEX/CIMEX 79

With this experimental system we participated in WINTEX/CIMEX 79 for a test under exercise conditions. Why was this participation decided, which did cost time and money?

5.1 Objectives for Test in Exercise

The first reason is to increase the military (and civilian) user's understanding for ADP and CCIS. That includes the realisation of the facilities and limits of these technical means, as well as the pulling-down of barriers of non-existing capability and good-will. In theoretical and even practical instructions we still make the experience that the potential users are still sceptic towards the "black box to which they do not want to surrender".

The investigation and evaluation of the technical functions of a system towards completeness and effectiveness as well as integrability into C^2-process under real conditions is a further objective.

Perhaps the essential reason is the determination of the preconditions to guarantee an effective and smooth performance. These preconditions include organisation, procedures (e.g. security procedures), legal problems (e.g. the privileges of the PTTs) as well as methods and extent of training for system personnel and users.

The obvious objective is the evaluation of information requirements and the implementation under real world conditions.

5.2 Exercise Preparations

The preparations started in summer 1978 and lasted till the last minute before begin of the exercise in March 1979.
After financing was clarified based on the preplanning of hardware and software necessities the actual preparations could start.

Because there was no exercise equipment available, most of the hardware had to be procured in and for a short time. Procurement of the central hardware was no problem, because we could use the computer of our institute. But to get the equipment for the 5 terminals was a rather big problem, especially under the short-time conditions. To get the cryptographic devices for the secured communication lines was feasible, because of an existing pool in the German MoD. But further more we were forced to rent communication lines from the German Bundespost who was not quite willing to switch the lines for only one month.

As far as the system and the data base is concerned, there is to say that we had the EMFIS system software available which is quite reliable. To talk about the application software and its preparations is another story. There was a tested software existing, but organisational and procedural changes in the area which should be supported made

it necessary to adapt the programs within a short time. In addition the data for the initial situation of the exercise had to be put into the data base.

Personnel for the exercise for an around-the-clock-operation had to be found and trained. Operators came from an operators platoon of the Air Force and needed only a short instruction. The job of the systemcontroller was taken over by experienced EMFIS specialists, because this is an important function for system readiness and security. Advisers had the function to help the users at the terminals in this first employment of the system.

All these people had to be trained especially systemcontrollers and users. For these two groups manuals are existing which had to be updated. The 3 systemcontrollers had the chance to get trained in test and practical instructions. The training of the users was quite shortcut, consisting of one theoretical and one practical instruction and 6 hours pre-exercise. But the manuals and the first days of the exercise helped them to get skilled.

There is really no necessity to mention that security plays an important role in military systems. All personnel had to be adequately cleared, the electronic security of the computer centre of the institute had to be measured and stated as well as the security of the communication lines and the cryptographic devices. Security procedures had to be worked out.

5.3 Exercise Hardware Configuration

The exercise hardware configuration (Fig. 4) consisted of the computer of the institute, a Siemens 7.748 with data transmission control. In the computer centre there was one terminal for the system controller with visual displays unit (VDU) and printer.

Remote terminals were with user A and User B at the German MoD in the first phase of the exercise and in the bunker of the government in the second phase. User A had a terminal with VDU and Printer, User B a terminal with VDU and teletypewriter for here a punchtape had to be prepared which was compatible with the normal Bundeswehr teletype network, so that orders could be distributed. The terminals were connected with the Centre by rented data lines resp. teletypelines secured by ELCROBIT or ELCROTEL. The lines were rented from the Bundespost and switched when the users moved from MoD to headquarter.

5.4 Exercise Experiences

The main experiences made in this test in exercise can be summarized as follows:

- The system was used parallel to the conventional procedures, so that a comparison was feasible between conventional and ADP-supported information flow. The ADP-supported information flow and situation monitoring was faster, but what was more important, it was more precise and free of errors.

- The time in which the user got accustomed to the system was amazingly short. We think this was due to the formatted inputs and to the fact that the conventional procedures were implemented in the application software as much as possible or reasonable.

- There was an unexpected high number of indirect users, i.e. users which needed the information as infoees and which could better be supplied than in a conventional system.

- Especially the objective to gain understanding for the use of ADP-supported CCIS could be reached because there were opportunities to demonstrate such a system under real conditions to several groups of visitors.

- Hard- and Software worked well through the whole exercise.

- The systemfunctions of EMFIS proved reasonable, especially that of the systemcontroller, i.e. to have human function highly computer-assisted to control system readiness and data security.

- Negative experience was the quality and stability of the communication lines which we got from the Bundespost. This escalated up to complete destroy of a line by road construction. The best ADP-supported CCIS is only as good as its communication lines. Positive result of this was the flexible reaction of the system EMFIS towards these malfunctions.

- The test has ensured our conclusion that application software adapted to the C^2-process needs continuous maintenance, because any change in organisation or procedures has an impact upon software. But only this way allows an effective support to the C^2-process.

6. CONCLUSIONS

I have started this paper in quoting some conclusions about man-machine interface in C^2-process and would like to extend these conclusions by my own.

- The support of the C^2-process by computer is a complex problem, which leads to a complex development process. This makes a continuous dialogue between user and developer necessary.

- In order to break the complex process down to reasonable development steps, it is necessary to have a long-term concept but a short-term, step-wise, modular implementation.

- Only pragmatic proceeding rouses understanding and motivation of the military commander.

- The development of ADP-supported CCIS is connected with the development of adequate communication systems. But do not forget to consider that in the past communication-systems were rather determined by engineering progress and were offered to the military commander, whereas the development of CCIS should be marked by the fact, that it needs the close cooperation with the military commander.

All people working in the development of ADP-supported CCIS sometimes come to the conclusion that it is a nearly unsolvable task. But the deluge of information as well as the fact that reaction time becomes shorter and shorter, force us to find the right way to solve these problems.

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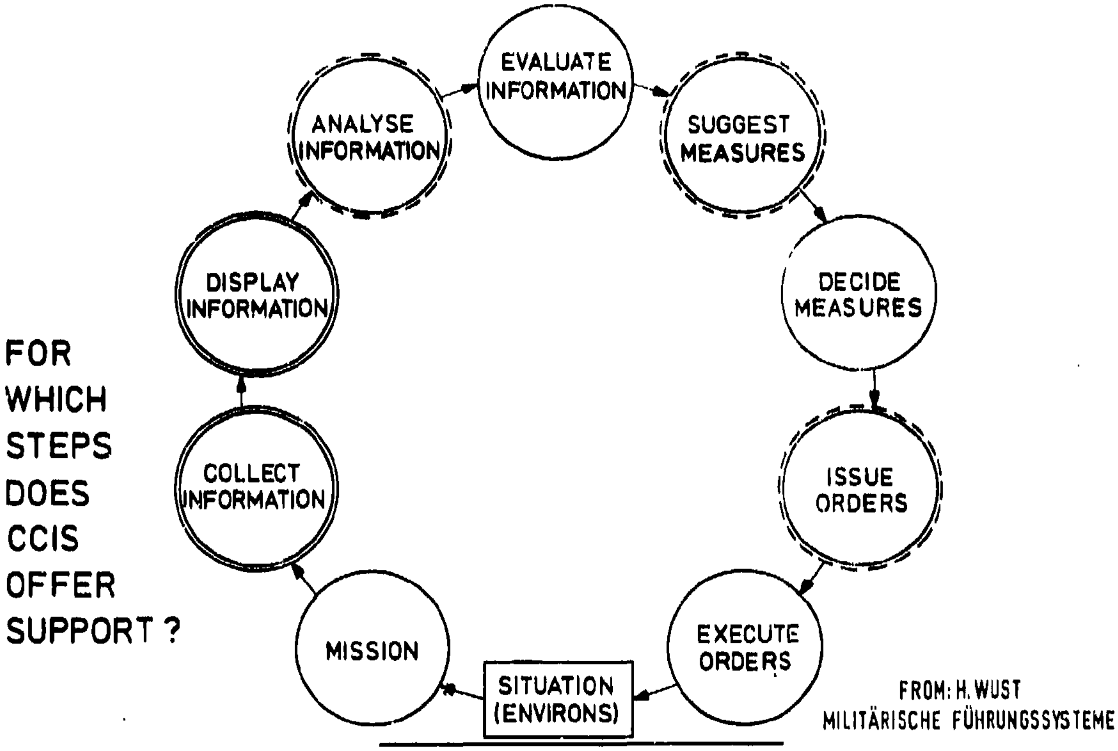


Fig. 1: C^2-Process

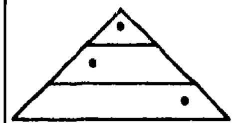
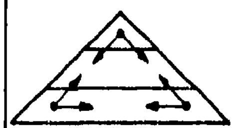
APPROACH	ADVANTAGES	DISADVANTAGES	SYMBOL
INSULAR APPROACH	- SURVEYABLE PROJECTS - FAST DEVELOPMENT	- LACK OF INTEROPERABILITY	
TOTAL SYSTEMS APPROACH	- OPTIMIZATION OVER TOTAL ORGANIZATION - INTEROPERABILITY	- COMPLETE DETAILED ANALYSIS - LONG DEVELOPMENT - SUPERHUMAN MANAGEMENT	
ALIGNED INSULAR APPROACH	- GENERAL CONCEPT - SURVEYABLE PROJECTS - FOCAL POINTS - SURVEYABLE INTERFACES - DELEGATED RESPONSIBILITY	- DEPENDENT ON CAPABLE MANAGEMENT - DEFINED INTEROPERABILITY	

Fig. 2: Development Strategies

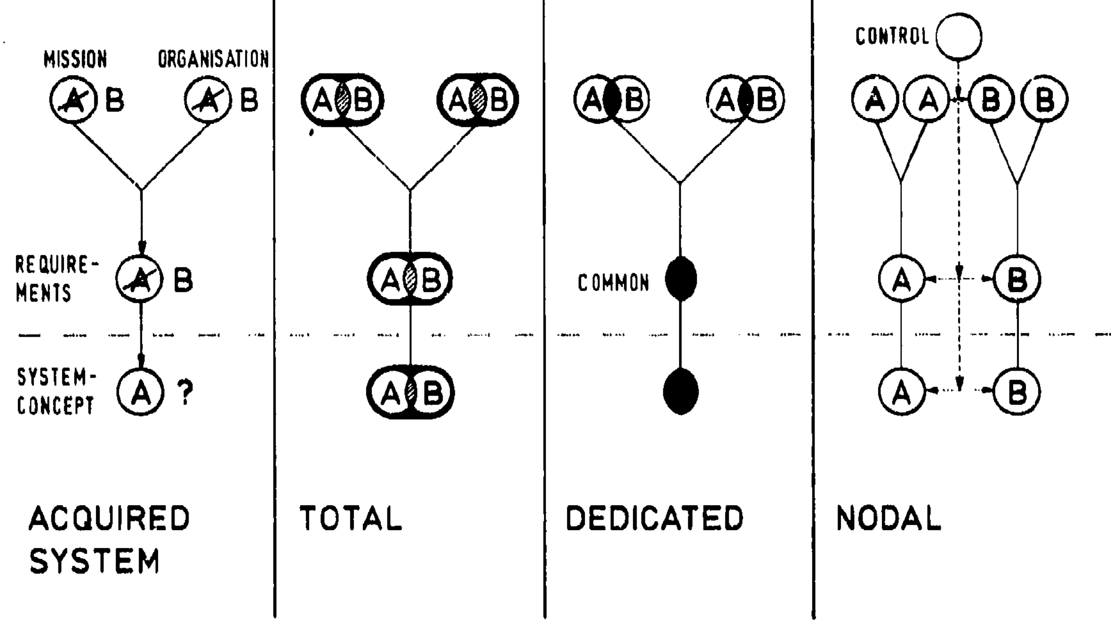


Fig. 3: System Concepts for CCIS

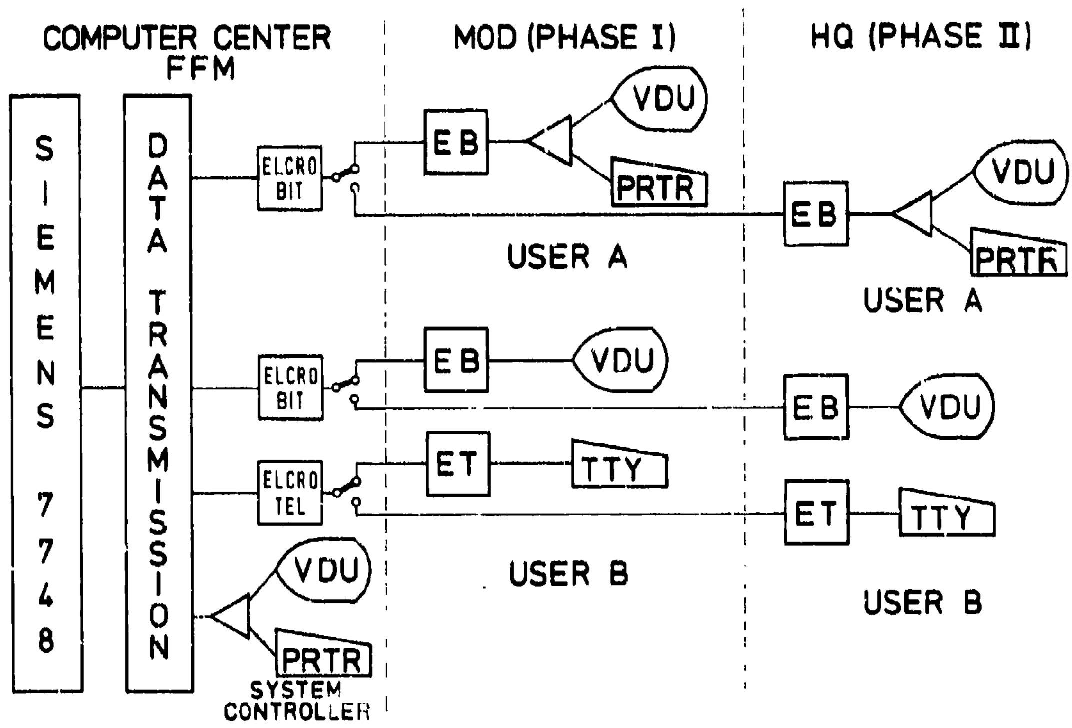


Fig. 4: EMFIS Hardware Configuration

SIMULATION OF OVERALL AIR DEFENSE COMMAND & CONTROL

Dipl.-Ing. Reinhard Hutter
Industrieanlagen-Betriebsgesellschaft mbH (IABG/SOL)
8012 Ottobrunn
Germany

SUMMARY

The scope of studies and simulation techniques in the area of Air Defense (A/D) broadly reaches from detailed technical simulations of system components (e.g. radar detection, missile flyout, aircraft vulnerability) up to theater level air defense war games. Only few activities are known which try to comprehensively include Early Warning and Command & Control (EW/C^2) into closed operations analysis type air defense simulation models.

This paper describes the achievements of a study which is tasked to provide a computer model that quantifies the effect of EW/C^2 in terms of active air defense Measures of Effectiveness (MOEs).

The model discussed includes the main technical and operational procedures which will be followed in air defense in case of an air attack

. information acquisition on hostile targets and counter weapons

. evaluation of the tactical situation(s)
  (air picture and own status)

. weapons allocation decision(s) and control

. evaluation of results.

The model is rather aggregated, highly input oriented, independent of specific systems and doctrines and thus offers flexibility of application to various technical and operational questions. The development status of the models is discussed as well as the main problems faced during the design and those still ahead.

1. GENERAL SITUATION

1.1 History

The core effort of analysis as described in the context of this paper is the development of computer models to simulate the operational and technical behaviour of air defense command & control systems. With respect to brevity, emphasis in this paper is concentrated on the operations analysis part of the described task. Development and application of tools for the evaluation of technical feasibility of systems or systems components and for the generation of input data for the OR-Model are running in parallel with comparable endeavor. The history of operations analysis and research demonstrates a slow but continuous progress towards the modelling of more and more complex systems, system mixes and system structures of highly interdependent individual system units. The basic steps which were passed throughout the last 10 to 15 years can be summarized by

. models for individual systems
  (1 on 1 or one on few engagement models)

. models for multiple systems

. models for system mixes

. theater level models including weapon systems and command & control systems and their interactions.

Fig. 1 tries to give a qualitative indication on the increasing complexity of the problems and associated models.

Numerous models have been developed providing adequate tools for the preparation of decision support at the various stages of the development and procurement process of matériel, with one major exception, which is the integration of command & control into a "closed simulation". Several problems have been faced which discourage us from undertaking this effort:

. Complexity:
  The complexity of a system such as the Integrated Air Defense and the impact of C^2 are not well enough understood by analysts.

. Uncertainty:
  The uncertainty about the commander's decisions cannot be modelled.

. Significance:
  The question whether or not results of a "Command & Control Model" will be significant with respect to the uncertainties named above can only be answered by experimenting with such a model.

- Measures of Effectiveness (MOE):
  Simple MOEs (e.g. averaged radar ranges) are not adequate to evaluate the effectiveness of Early Warning and C^2. Complex MOEs (e.g. contribution of C^2 to the number of hostile targets killed and to the number of own assets surviving) require the inclusion of all A/D elements and their interactions, which leads to extremely large and expensive models.
- Theory:
  There is no theoretical basis available on Early Warning and Command & Control.
- Resources:
  Lack of computer resources prohibited models of size and complexity adequate to the C^2 problem.
  A study of this complexity offers a relatively high risk with regard to cost and success.
- Study Policy:
  A study which ultimately quantifies the effect of command & control might question the benefit of existing or planned systems and the validity of existing C^2 doctrines.

1.2 At Present

Only few activities have been recognized which try to provide quantitative measurement of air defense command & control effects. However, the time appears to be mature for this step forward.

- Extensive on going and past weapon system analyses provide a sound data base and good experience for the engagement part of an overall air defense model.
- Size and speed of computers available promise economic handling of complex problems.
- Increasing expenses in the air defense EW/C^2 area more than ever demand the quantitative proof of the effectiveness of those systems.

1.3 Outlook

The study activity presented in this paper is a promising approach to simulate the integrated air defense within one self contained simulation model. It will include all basic components of ground based and airborne weapon systems and EW/C^2 systems und functions. A first version of the model is presently in the final development phase.

2. DISCUSSION OF THE PROBLEM

2.1 Measures of Effectiveness (MOEs)

The keys to the structure of any OR-Model ultimately are the degree of detail desired and the measures of effectiveness to be used. For complex systems, however, one MOE only will not be adequate to answer all potential questions to be investigated. In our case, the MOE(s) must serve the purpose to measure the effectiveness of EW/C^2 in terms of the effects on air defense performance. Frequently used terms such as radar ranges, track quality, completeness of the air picture, reaction times, etc. can be used to analyze and optimize subsystems, as these MOEs express the performance of components, however, they do not measure the effectiveness of the total system. As for the latter the classical MOEs for air defense can be applied:

- number of hostile targets killed, total and by target type
- number or probability of own air defenses and assets killed
- number of red and blue weapons expended, by target type
- number of uneffective engagements; reasons for failure, etc.

For complex problems more than one MOE must be applied in order to gain a complete picture of the effectiveness, and the problem remains usually with the customer, how to combine these results to higher aggregated numbers or decision variables. E.g. killed A/C are hardly comparable to the tactical value of surviving command posts. Even higher aggregated and more pretentious MOEs can be defined such as:

- endurance of a defined minimum air defense power over a certain time period
- contribution of air defense C^2 to the FEBA movement
- deterrence effects.

To find numbers for this kind of parameters, however, is either impossible or requires extensive and extremely sophisticated and expensive war gaming techniques. A closed simulation, thus, will be restricted to a selection of those "classical" MOEs for air defense as listed above (killed A/C etc.). If, however, a simulation model, including command & control, can provide a quantitative measurement of the effectiveness of C^2 by these MOEs this can indeed be considered a step forward in analytical evaluation techniques for military systems.

Above that it seems to be impossible to define the "ultimate purpose" of the C^2 system, yet, the ultimate purpose might vary from one conflict type to another.

This leads to the discussion of some critical points in the task of modelling air defense C^2.

2.2 Specific Problems and Restrictions

Although the conditions as they developed throughout the last years are promising with respect to C^2 modelling, some major problems still have to be analyzed and understood. A first "Integrated Air Defense Simulation" will still suffer from some shortcomings and restrictions since the task has to concentrate first of all on the overall structuring of the problem and on the basic approach rather than to try perfection at each individual module.

It was well understood, that there was no exact definition of air defense C^2 available which could be taken as a baseline for the approach. As will be explained later in more detail, the methodology developed is a rather pragmatic sequenceing of the major technical and operational functions of air defense and its C^2, which are supposed to be:

- . surveillance/target detection
- . aquisition and update of target information
- . processing and distribution of air picture data
- . analysis and evaluation of the threat
- . monitoring and evaluation of the status of own air defense systems
- . alerting of air defense systems
- . allocation and coordination of weapon systems engagement
- . monitoring and evaluation of engagement results and consequences.

This approach, consequently, excludes the simulation of high level political and strategic decisions. They will be merely regarded via input such as status files, weapon resources available, etc. at the beginning of an anticipated conflict.

The simulated time slice of a conflict must be limited to an interval which allows redeployment and reorganizing of the air defense resources off line between individual computer simulations. This is necessary, as no dynamic redeployment algorithm could be developed up to now.

There is almost no value in modelling air defense without including at least the basic types of countermeasures. However, the step from benign to an even rather simple ECM environment considerably increases the complexity of the model and the cost and manpower involved. Simulation of an ECM scenario may multiply the number of computer statements to be executed by a factor of 10 to 50 as compared to a benign environment.

A similar degree of complexity offers the IFF problem. Neither theoretical nor experimental data are available on the reliability and the dynamics of future IFF systems when operating in dense scenarios including ECM. The approach to the IFF process in theater level air defense models is necessarily rather simplistic. The logic of threat evaluation and hostile target classification will be explained later in the course of the model discussion.

Another uncertainty which has to be faced is the high degree of freedom vested in the commander during the evaluation of tactical situations and at the events of decisions: Only preprogrammed decision choices can help to reduce the variety of possibilities. It is, however, hardly impossible to define a priori effective doctrines for future weapons and C^2 systems, whose technical and operational characteristics may differ considerably from those in use today. Only a qualified judgement together with iterative or interactive use of the simulation will lead to a limited set of doctrines corresponding to future systems.

3. THE MODEL

3.1 Basic Principles

A variety of technical and operational functions of an EW and C^2 system can be subject to evaluation. Some examples of evaluation at the "information acquisition level" are:

- . performance of alternate sensors
- . capacity of data links
- . degree of integration or netting of individual sites etc.

On the level of "information analysis and utilization" other evaluation areas are of interest, such as:

- . logic of threat evaluation
- . alerting procedures
- . doctrines of engagement coordination etc.

Many more subjects can be defined as will be seen later. In the sense of evaluation, common to all of these - very different - elements is the demand to be ultimately measured in one or few terms of air defense effectiveness equivalents.

This postulates a highly flexible computer simulation tool which must follow some basic principles:

Independence
The overall model as well as its subparts must not be tailored towards specific systems in the sense of systems hardware and software nor with respect to rules and doctrines. None of those will be "hard wired" in the model.

Completeness
As already mentioned before, the model must be capable to simulate and evaluate all important components of air defense C^2 and leave the actual application to the choice of the user. The same principle applies to the output parameters.

Flexibility
The model must be capable to simulate mixes of different land based and airborne weapon and C^2 systems, including their interconnections and interactions.

Size
Only the simulation of rather large and complex scenarios is adequate to the evaluation of Air Defense C^2 systems.

Consistency
The individual modules of the model must be of balanced resolution. Only for special purposes a program module with a degree of detail higher (or lower) than the remaining parts should be inserted.

Handling
Input and output of the model must be easily changeable in order to allow quick variations of the simulated systems, scenarios and doctrines. The turnaround (generation of input, computer run, evaluation of results) must be short and sufficient numbers of statistical replications must be produced at reasonable cost.

An experienced defense analyst giving a first judgement to these postulations will conclude that at least some of them are contradicting or even excluding each other. The key, however, to the compromise of a first approach is to limit the complexity of the "integrated model" and to strictly separate between this model and the resources and models required to generate the input data.

By the way - the complexity of the overall task requires a rather heterogeneous team of analysts of very different disciplines. Hence it is sometimes more difficult to force the study team members to stick to the principles of the approach rather than to define the model itself along the lines of these principles.

3.2 The Model Structure

The overall model structure follows the lines of the "classical" functional process of air defense operations consisting of the three main blocks (see fig. 2):

. air situation

. allocation

. engagement.

In figs. 3 and 4 the blocks of air situation and allocation, respectively, are broken down into their program modules each of which is representing a major function within the air defense EW and C^2 system.

These individual submodels are controlled by a general frame program. It exclusively executes organizational tasks. It provides input routines, output monitors and data management service, and the control of the individual submodels.

Regarding the variety of air defense C^2 systems and the different nature of their subsystems to be included in one model, the control of each of the submodels was decided to be optionally either strictly time step oriented, event oriented or mixed mode.

This allows the realistic and economic simulation of periodic processes (e.g. radar rotation, cyclic data transfer) as well as asynchronous events such as engagements and kills, waiting queues, etc. The internal feedback loops of the model are not shown in the figures.

Returning to figs. 3 and 4 the following chapters give a short description of the model modules (left hand column in figs. 3 and 4) and the associated types of input data and methods of input generation (right hand column).

3.2.1 The Scenario

The Red scenario is composed of up to 250 "flights" of targets which can be either single A/C or formation targets. Each flightpath is a polygon of legs with variable flight parameters (altitude, heading, velocity etc.) per leg. A/C or formations are further characterized by their radar cross section, number of A/C, and jamming status (ESJ and SSJ). In addition, racetracks of stand off jammers (SOJs), ground based jammers, and chaff areas can be deployed.

On the Blue side, up to 30 ground based Early Warning radars and 5 flight patterns of Airborne Early Warning radars can be simulated. Each of the radars is usually but not

necessarily co-deployed with a C^2 site. Data processing capacities and communication networks between EW/C^2 sites themselves and C^2 to weapon systems communications facilities and their capacities are defined by input. Certain areas of responsibility for track maintenance and crosstell - so called track production areas and track continuity areas - are assigned to each site.

The terrain model is based upon probability distributions of target unmask ranges as a function of target altitude. Different distributions can be input depending on the category (rough, flat etc.) of terrain surrounding the site.

The Blue air defense weapon systems - the various classes of ground based air defense systems, and fighter units - are characterizes by their deployment, the readiness status, the control state, and by their performance data as far as required for the weapons allocation process.

3.2.2 Target detection

Depending on the actual application task, the detection can be simulated in two optional ways which substantially differ by the degree of detail:
Both, the "Multi Radar Model" as well as the "Simplified detection by Area" can be run on-line within the overall simulation.

The Multi Radar Model uses the detailed technical data of the radars and calculates the physical detection process (signal to interference ratio) of each individual target regarding the target data and its electronic and geographic environment. The output is basically the single scan detection probability and target resolution status.

As they include the physical effects of main beam and sidelobe interference of active jammers, clutter and chaff effects and the accuracy of measurement, these results are rather exact and realistic, however, at the price of relatively high computer cost.

The detection by area assumes that in specific environmental areas, e.g. in the foreground of chaff, within the spoke of an SOJ etc. the average detection probability by radar can be expressed as a function of target radar cross section, its distance to the radar, its altitude, and a few other target and radar parameters.

These parametric data of single scan detection probabilities are precalculated by the detailed radar model for those parameter combinations which actually occur in the scenario. Detection probability envelopes calculated for test scenarios proved this approach to be feasible (see fig. 5).

This method allows the precalculation of the history of intersections of the flight paths with the boundaries of the different detection areas in advance of the combat simulation for each target versus each radar (see fig. 6). The detection simulation itself is reduced simply to finding out the actual set of parameters for the simulated point in time and for each radar/target combination and to drawing a random number against the corresponding detection probability.

Jamming targets, when covering the radar's frequency band generate a jammer strobe as soon as they are in radar-line of sight and as long as burnthrough cannot be achieved by the radar. The strobes are maintained in the strobe file for further processing.

3.2.3 Tracking

The tracking model is a fast running tracker which includes all degrees of freedom of real tracking logics with the exception of the detailed mathematics of the filtering process. Implementation of filters into such a model is not proposed for two reasons. First of all, the flightpath input data do not describe the target trajectories in sufficient detail and secondly, modelling of filters would exceed the desired grain of the overall model. Similar to the principle applied to the simplified detection simulation, the filter performance will be regarded by so called reduction factors which are calculated off line by detailed programs representing the tracking logic of the real systems to be investigated.

Input to the tracking model is the sequence of target plots per radar and target as generated by the detection model. The type of track initiation and track maintenance/track quality calculation logic can be specified by input.

As the result the so called track quality matrix specifies for each tracking site, which target is in the initiation process or in the system track file and which quality is assigned to it at the simulated point in time.

3.2.4 Data Processing (DP) and Data Communication (DC)

The task of this model is to simulate the behavior of data processing and communications equipment. The network of C^2 systems is specified by the so called communication matrix and its associated link and data processing capacities. The data generated by the detection and tracking model is transformed into the workload of the communication net and its processing centers which requires further information on message lengths, overhead procedures, processing times per track etc., which have to be provided to the model from off line analysis or - when available - by measurements at the systems considered.

The DP and DC models are processing the following types of information or messages:

. system tracks

. tracks in the initiation process

. strobe tracks

. crosstell inputs and outputs
(ground to ground, ground to air, air to ground)

. C^2 messages

. overhead factors

. basic load profile for messages/processes other than those above

The DC part of the model periodically simulates the time delays and information losses occurring in the crosstell network by a queueing and filtering logic. Main emphasis is paid to the track data crosstell and the update process of the air picture at the sites participating in the network.

For each processing cycle, the DP model accumulates the actual workload generated by the elements listed above. From the past and momentary load of the processing units, delay times particularly those of the air picture data are determined.

The DP/DC model finally delivers the air picture as it develops in all sites and centers of the EW/C^2 system simulated.

3.2.5 Jammer Strobe Processing

At present, the strobe tracks are maintained as part of the air picture file. Sophisticated techniques for ranging the jammers such as triangulation and correlation procedures cannot be modelled yet, since no sufficient experimental nor theoretical experience is available about this problem. Mathematical approaches to simple jamming situations are relatively easy. Solutions to the problem of large, jammer rich scenarios must still be developed, which must combine the mathematical/technical support (triangulation) with tactical judgement and measures in this jammed areas.

The data base for a first "Triangulation Model" will be time delays, load factors for DC and DP, probabilities for positive ranging, and probabilities of ghost targets. For a specified radar and its computer, all of these data mainly depend on two factors: The absolute number of jammer strobes and their relative density.

3.2.6 Air Picture Analysis and Threat Evaluation

The analysis and evaluation of the air picture is the interface between the passive part (information acquisition) and the active part (counter actions) of the air defense. The problem of this part of the A/D game is that it is impossible to include the judgement processes, the experience of commanders, and all their objective and subjective aspects into a simulation, except by a man - in the - loop model. Many different empirical threat evaluation formulas are available from specific air defense systems, but they are not applicable to a general air defense model.

The closed general simulation model hence, must be restricted to the combined assessment of the most important parameters of the air picture. The model offers the basic evaluation and decision methodology. The evaluation parameters, however, must be selected by the user as must be the importance (weighting) of these parameters and their logical combination.

Some of the usually regarded parameters are e.g.

. target position relative to the FEBA

. target altitude

. target velocity and heading

. total number of targets

. number of hostile targets

. concentration of targets etc.

Other factors such as strategic situation, availability of own forces, knowledge about own deficiencies etc. might - more indirectly - contribute to the threat evaluation too.
In order to leave this flexibility of choice and combination of parameters to the user, the decision table principle was selected as a general purpose methodology for the threat evaluation model. As can be seen from fig. 4, three different steps of threat analysis were isolated:

Evaluation by hostile criteria:
In this usually rather early step of evaluation, each target is checked whether or not it meets the so called "hostile criteria" such as number, position, heading, etc.

. Air picture evaluation:
The assessment of the overall air picture must include the additional criteria: Total number of targets, concentration of targets, political assumptions, etc. This evaluation phase results in decisions on the alert and readiness status of own air defense forces.

. Threat ordering:
Another target by target evaluation must be executed in order to judge the threat which can be expected from the individual targets of the attack, resulting in target priority numbers or alike. This phase provides the basic evaluation of the threat as an input to the weapons allocation process.

An example of a decision table input and some decision alternatives for the threat ordering evaluation is shown by fig. 7.

All the three threat evaluation routines are called periodically by the frame program. If desired or reasonable, the time period can be different for each routine or it can even vary throughout the simulation, which allows an assessment adaptive to the actual situation.

3.2.7 The Alert and Combat Readiness Model

The core of this part of the simulation is the decision table discussed already. Each decision center is responsible for the command of a certain area with its air defense weapon systems deployed. The number of centers and the size of the area is a first order means to determine the degree of control centralization. The model monitors the readiness status of the weapon systems and provides the transition from one status into another one if so decided. The readiness status can be structured the same way as the presently valid Defense Readiness Postures or differently, which will be particularly necessary when future weapon systems are considered.

Furthermore, the model monitors the availability of the weapon systems resources which depends on one hand on the alert status and on the other hand on the actual engagements and engagement results.

3.2.8 Engagement Allocation and Coordination

Up to this point of the simulation, the two elementary resources for the weapons allocation process,

. the evaluated air picture and

. status and availability of A/D systems

have been prepared.

In addition, the performance data of the weapon systems (range, rate of fire etc.) and the communication facilities from the command centers to the weapon system units must be input to the allocation model. The allocation model has to best utilize these four types of information in order to serve the chosen measure(s) of effectiveness. In principle, one could think of the possibility of analytically optimizing the allocation of Blue vs. Red forces by trying to maximize or minimize the respective objective function which generally has the same dimension as the MOE applied. It was, however, realized that there is no straight forward optimisation possible,for the following reasons:

. At the time of allocation decisions, the result of the decided measures are not deterministically predictable, as the situation may change during the execution of the decided action.

. A sequence of decisions which are optimum at the individual points in time may not necessarily lead to an overall optimum effectiveness of the air defense battle. E.g. a high initial engagement ratio can result in a maximum achievable number of killed targets (which might be the temporary objective function), however, there might be no reserve available to cover a second attack wave (which might contradict to the overall objective function).

. It must be possible to evaluate optional,predefined allocation doctrines. An optimization algorithm would prevent this flexibility.

Although at the closing date of this paper the allocation model was not completed yet, the basic approach, has already been defined (see fig. 8).

The model must provide a basic software which allows the execution of various types of allocation rules and restrictions, selectable by the user of the model. Some examples of rules are:

. engagement by area (e.g. fixed weapons engagement zones)

. low targets preferred

. no simultaneous engagement of the same target by fighters and SAMs allowed

. only one (two ...) engagements per target

. engage as many targets as possible

. Combat Air Patrol (CAP) policy, etc.

Using the status files and the air picture as input, first of all, a series of alternate potential allocations is calculated. This calculation mainly regards the engagement volumes of the weapon systems in question and, in case of SAMs, their rate of fire and missiles available. In case of fighters, the operating ranges and the available numbers of sorties are regarded. This general allocation part also accounts for the dominating policy rules which must be specified in advance of the allocation, e.g.

. prohibited areas

. distribution of fighters to certain rules (CAP, GCI etc.).

These restrictions will already limit the total number of potential allocation combinations.

From these alternate allocation tables, an algorithm which regards the specific tactical rules and restrictions as listed before,and the available communication lines, selects at least one "reasonable" set of allocation decisions. These are affected by the decision delay times and are finally executed. As it is in reality this will be only one of various possibilities, the effects of which must finally be analyzed off line and manually be compared to the air defense objective function, whichever it might be, for the scenario envisaged.

The described method suggests the repeated use of the once generated general allocation tables (which is rather time consuming) without running the overall model again. Applying different sets of tactical rules in the later part of the model results in an accordingly greater number of allocation variants which provide a broader result basis for final evaluation.

The present model version does not simulate the engagement of the weapon systems. The outcome of the engagement is rather estimated from the rough performance data which were input to the allocation model. It is but left to the user of the model, to apply the engagement decision data as input to off line weapons engagement simulation models if more accurate effectiveness figures are requested.

3.3 Limitations and Improvements

Most of the model limitations and restrictions have already been discussed in the course of this paper, particularly in chapter 2.2:

. no dynamic redeployment during one simulation

. ECM is limited to noise jammers of the various types, and chaff

. only parts of the different IFF procedures are modelled.

The size of the scenario is limited but appears sufficient for the study questions expected.

Besides testing,experimenting,and actual applications of the first model version, significant modification and improvment efforts will be successively undertaken, which will concentrate on the following areas:

. modeling of triangulation

. inclusion of new technologies
(phased array-, multi static radars, multiple radar tracking etc.)

. emission control of sensors as an electronic countermeasure

. implementation of a group track routine

. refinement of event and queueing control of the DC and DP model

. refinement of the terrain model.

Problems are still expected with the acquisition of input data, as soon as specific air defense systems will be named for evaluation. Three types of resources will have to be utilized for input data generation or acquisition.

<u>In house capability</u>
Technical off line simulations, particularly in the area of radar detection, tracking, strobe tracking and triangulation, data processing, and data communications are partially available, others still have to be developed. They serve the purpose of input generation for the overall model on one hand and on the other hand these simulations provide valuable tools for the evaluation of technical performance and feasibility of systems or system components, respectively.

<u>Industry</u>
For systems in the conceptual or the development phase the detailed technical characteristics will be requested from the responsible companies.

<u>Measurements</u>
From simulated or real exercises or from testing experiments, life data of fielded systems such as delay times,loads of components, tactical decisions,etc. provide an additional data base for simulation or model verification purposes.

3.4 Areas of Application

Due to the principles as discussed in chapter 3.1, the model presented offers a wide range of application areas, which are orientated, of course, towards the overall model structure:

. radar types, deployments, mixes

. data processing and communication systems alternatives, network structures etc.

. threat evaluation doctrines

. weapon systems alerting procedures, engagement and coordination rules

. mixes of weapon and C^2 systems

. modes of control and integration of weapon and C^2 systems.

In these areas studies of different type can be supported by the methodology developed:

. feasibility studies

. sensitivity analyses of technical and tactical parameters

. comparison studies of alternate systems

. trade off studies of different subsystems against each other.

The measures of effectiveness can be chosen within the range of the classical air defense measures, as described in chapter 2.1. Output standards have not been settled yet. They will be developed within the course of further model improvement efforts.

4. CLOSING REMARKS

The challenging work undertaken, the development of a tool which quantifies the effectiveness of EW/C^2 in air defense, includes a relatively high risk of failure because of the complexity of the overall problem, and because predecessor efforts of this type are only available in some specific areas. So far it could be proven, that there is a possibility of modelling C^2 in the overall air defense in a general way. Yet, it has not been substantiated in which areas the application of the model can deliver results significant to the question and where not. A broad interest of users has been indicated for applying the model to actual questions arising in the planning process of air defense Early Warning and Command & Control systems.

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Fig. 1 LEVELS OF MODELLING
AIR DEFENSE SYSTEMS OPERATIONS

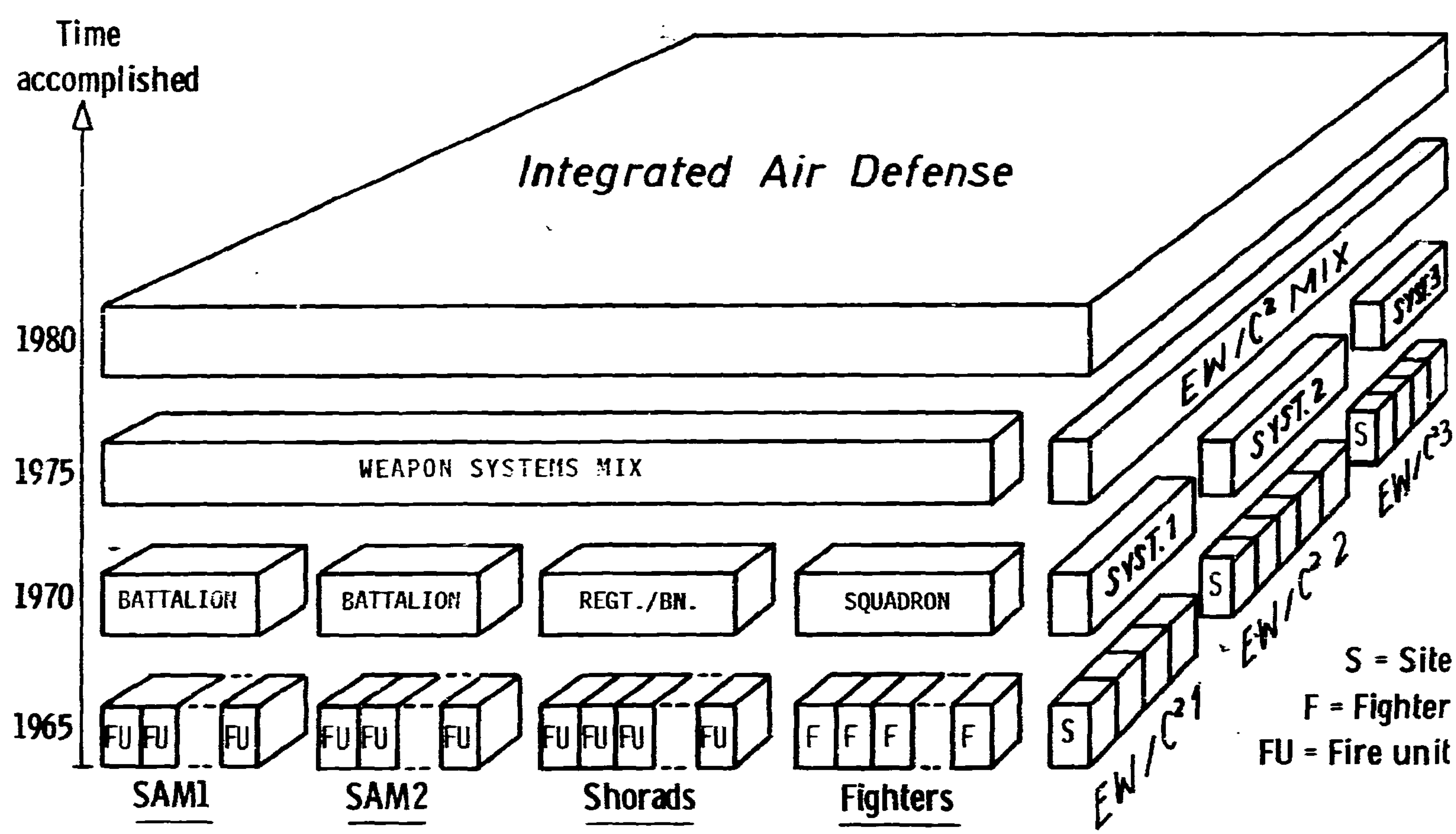


Fig.2 MODEL-STRUCTURE

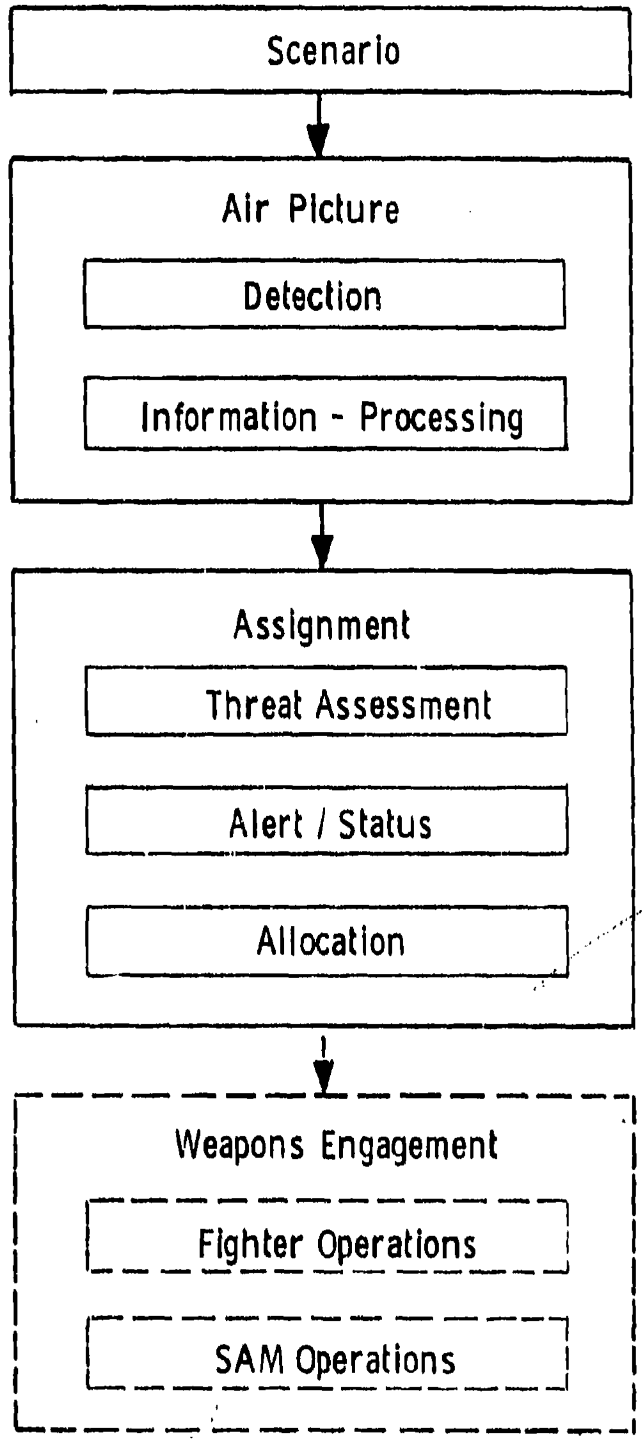


Fig. 3 AIR SITUATION MODEL

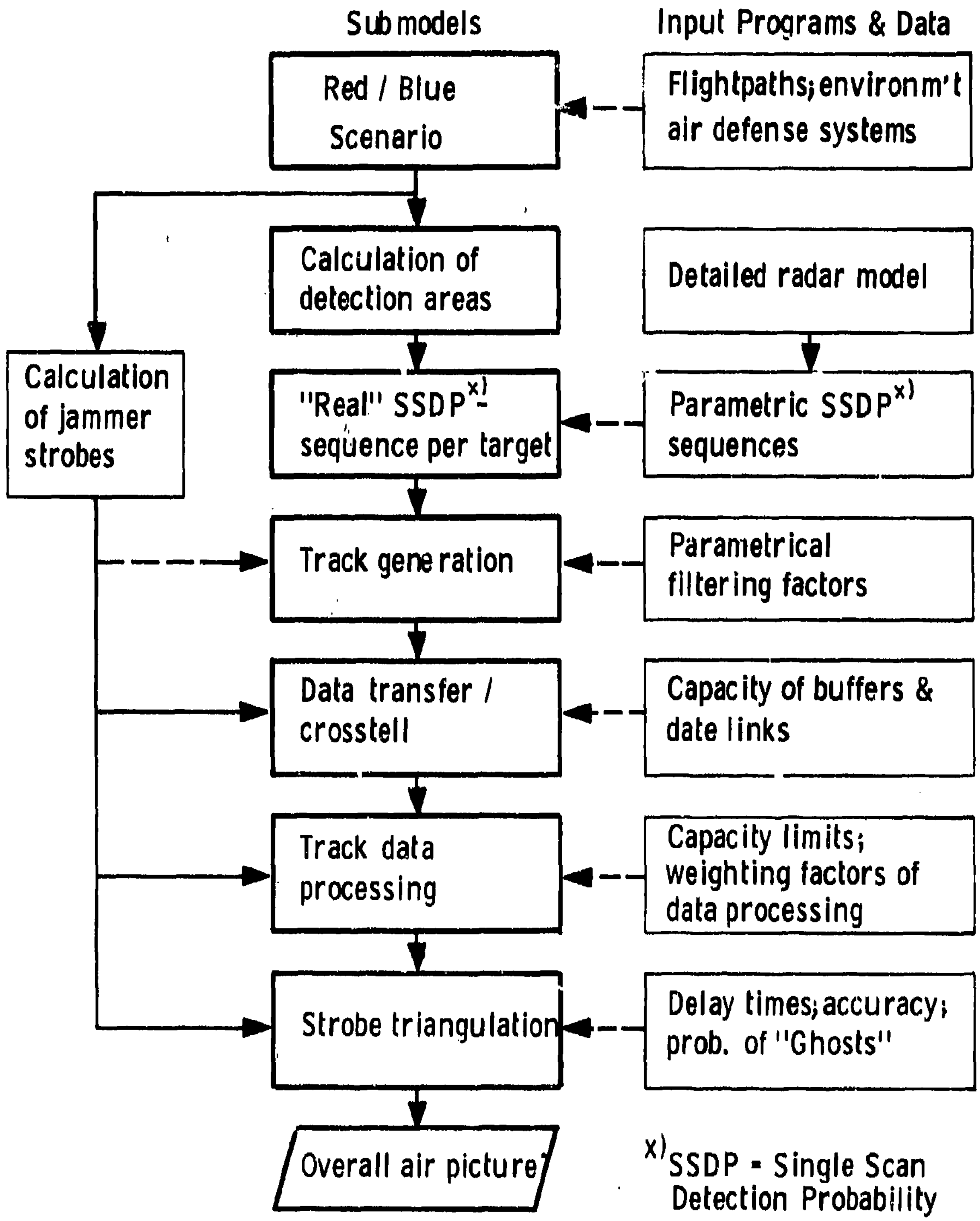


Fig.4 EVALUATION AND ALLOCATION MODEL

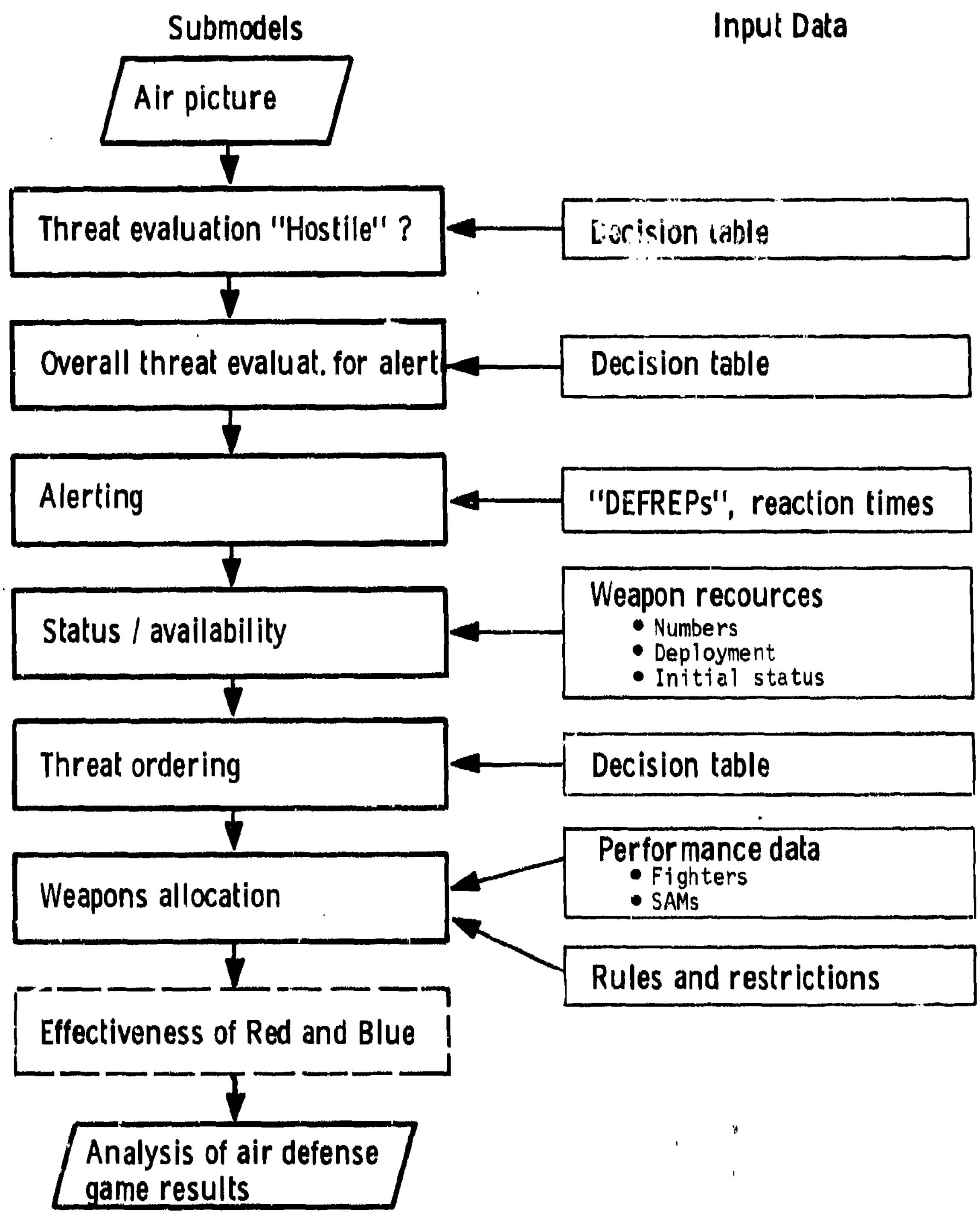


Fig. 5 MULTI-RADAR-MODEL

Parametric detection probability envelopes

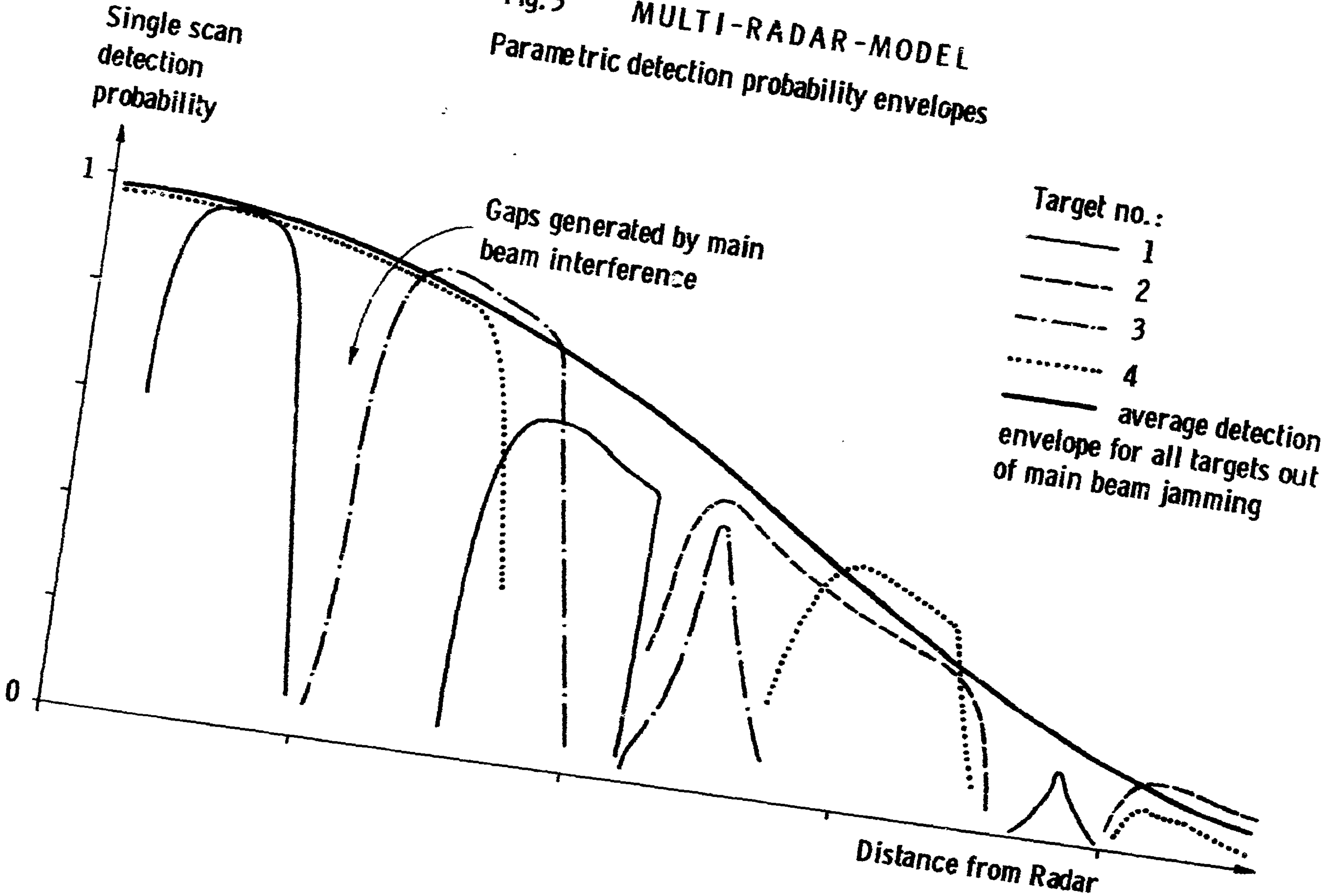


Fig.6 TYPICAL DETECTION AREAS

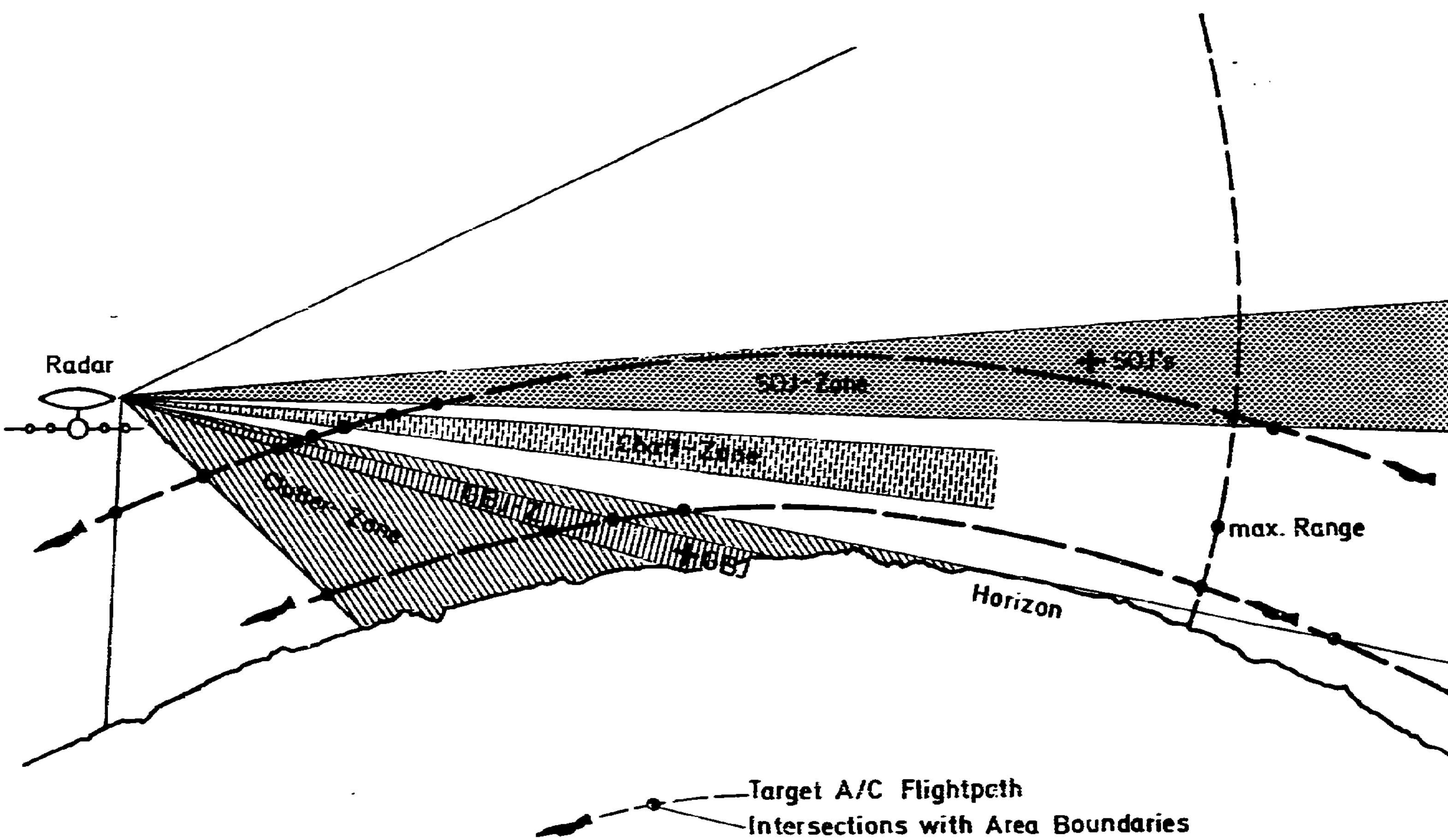
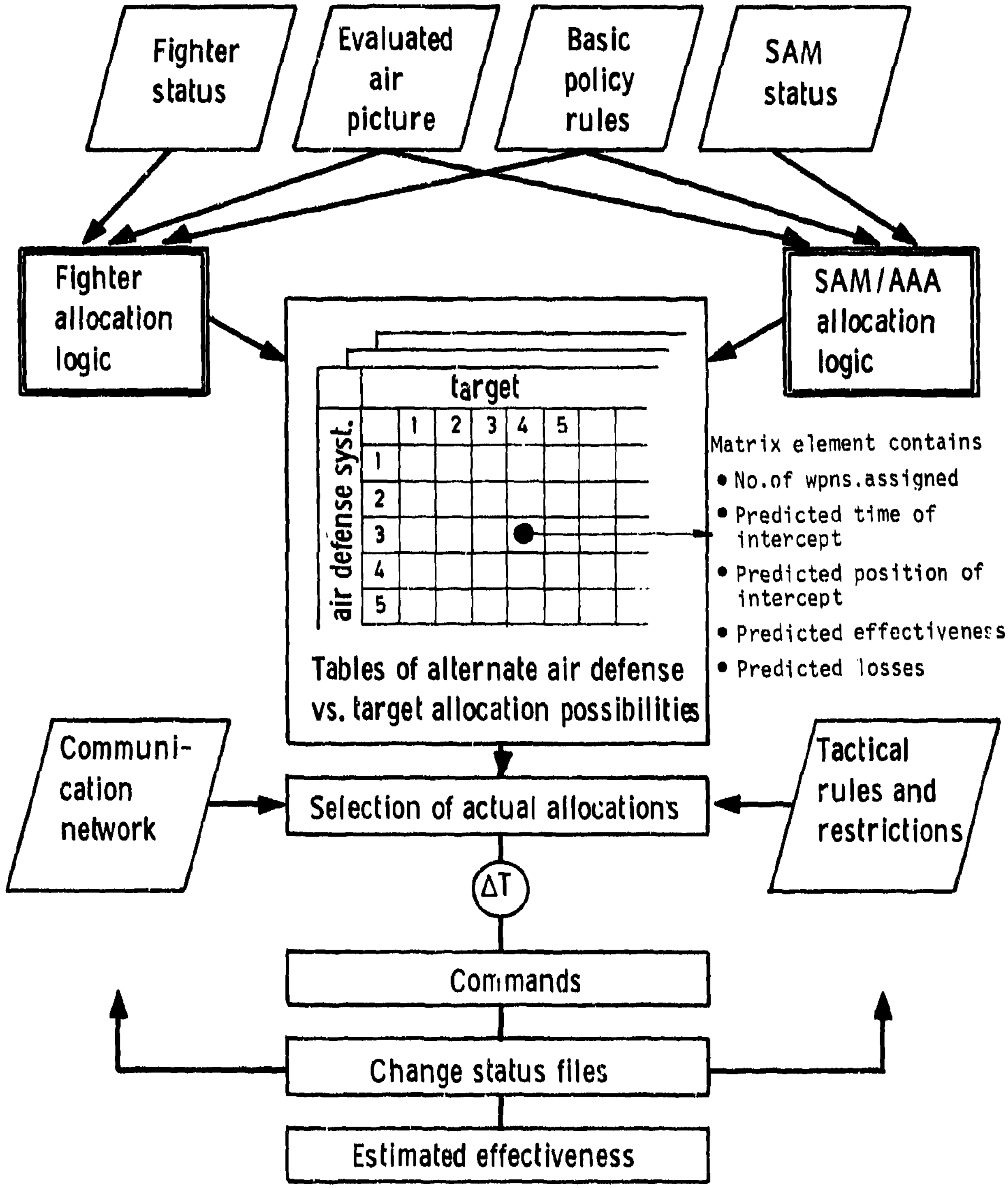


Fig.7 DECISION TABLE EXAMPLE FOR CONTINUCUS THREAT ORDERING

	Input Variable								Decision Variable
	nr. of "hostile" targets	estimated target size	target concentration	target heading towards blue assets	target east-west (x-) position	target velocity	target altitude	target jamming	threat ordering (priority)
Range of variables (input example)	1 1-10 > 10	1 1-5 > 5	"iow" "high" (Number of targets in specified volume)	"yes" "likely" "no" (to be expressed in degrees)	east DL "forward area" "rear area" (km)	< M .9 ≥ M 1.	low / very low med./ high very high (m)	yes no	0 1 2 3 4 5 6 etc.
Some examples of decision situations	10	1	low	"likely"	"east DL"	M .8	low	no	3
	30	5	high	yes	"forward"	M .9	med.	yes	5
	5	2	low	no	"east DL"	M .7	high	no	1
	1	1	-	no	"east"	M .2	med.	no	0

Fig. 8 THE ALLOCATION MODEL



THEATER AIR DEFENSE ENGAGEMENT SIMULATION-COMMAND/CONTROL/COMMUNICATIONS (TADENS-C^3) AN APPROACH TO THEATER AIR DEFENSE MODEL/METHODOLOGY DEVELOPMENT

Urban H.D. Lynch, Lt Col, USAF
Tactical Systems Division/SAGR, ID384
Assistant Chief of Staff, Studies and Analyses
Headquarters, United States Air Force
Pentagon, Washington DC, 20330, USA

Abstract

The needs for a single, flexible model that credibly simulates the critical elements/interactions in theater air defense are many and varied. The need begins with the advanced concepts planner who needs to know the first order "theater effectiveness" of an advanced system. The need continues with the high level defense planner who must make a critical decision on alternative systems to develop or manufacture. The need typically ends with the military user who is looking for the major theater tradeoffs as he attempts to best plan the employment of his resources against the threat. TADENS-C^3 is a theater air defense model/methodology development whose goal is to timely (Nov 80) produce a "credible, agreeable, and usable" model/methodology to address tactical (strategic) theater air defense and its associated problems/issues. The model development scope is designed to address NATO theater air defense. The minimum goal is to be able to address the NATO Central Region to include all allies. The management approach includes a single model manager (HQ USAF/SA) and a process whereby the analysis centers, system developers and tacticians of the several military/civilian services have a means to affect the credibility of the final model. It is this "process" that will hopefully make the model "agreeable" to the entire air defense community and potentially result in a single model/methodology "useable" by all greatly simplifying the study/analysis approach for the systems decision process. The nature of theater air defense dictates that the model/methodology "credibly" address such key interactions as follows: explicit C^3, ECM terrain, weather, airspace control, interoperability, procedural techniques, IFF, etc. The model is being built to address these interactions with a flexibility to not include a given interaction (and not pay the associated computational price) if the interaction is not wanted or needed. Specific attention is being given to methodology to model endgame attrition of flight on flight and flight on SAM/AAA array to make it as realistic as analytically practicable. The paper contains the need for the model, the model/methodology management approach, a description of the model interactions (specific attention on C^3 modelling), a list of typical problems TADENS-C^3 can address and the status/schedule of model development/use.

Introduction

Observations

- Technology is driving weapon/system development to more sophisticated, lethal, and costly weapons/systems.
- High lethality with its potential for misuse (against both foe and friend), dictates the need for higher level, more effective, command, control and communications, C^3.

- o High cost of new systems, given budget constraints, implies fewer resource numbers (most likely opposed by a quantitatively superior threat) which one cannot afford to misemploy but needs to be "multiplied" by skillful allocation through effective C^3.
- o But C^3 systems are also very costly, some very vulnerable, and one might potentially overspend on C^3 when he should be buying more resource numbers.

This circular logic leads to some interesting questions if one assumes the "law of diminishing returns" (see Figure 1).

Questions

- o Which weapons systems? How many?
- o How much C^3?
- o Is more resource numbers with less technology better?
- o What is the comfortable size of the military budget to at least assure a neutral outcome (i.e. where are we on Figure 1 which is very difficult to quantify?)?
- o What can the analyst do?

The Analyst Contribution

Because the worth of a military system must be measured in terms of its military utility/effect on battle outcome, the analyst is faced with modelling the large scope battle, its key interactions, and the contribution of military systems to those interactions. In essense, the analyst must quantify, within reasonable bounds of confidence, the tradeoffs implied in Figure 1.

The Analysis/Model/Methodology Approach

Systems Versus Learning/Issues Versus Interactions

The operations analyst is regularly faced with quantifying the military worth of a system (or several alternative systems) which is often related to a military defense "issue." As such, analysis and models can easily be heavily weighted to the system/issue at hand. The systems requiring study are often five to ten years into the future, involving high technology, with ill defined operations concepts and requiring answers now. As such there is little time for model development during a study and the analyst is often faced with making use of the limited tools and information at hand.

In the best of situations, the analyst has time to amply explore the system, issue and their interactions in relationship to the total military force; he also has a flexible total force model that has a "basis" (like a vector space) to capture the key interactions of virtually any system to be placed into the total force. A model with such a "basis" of interactions looks to the future and has a long lifetime of utility with limited need to modify the model or evolve it over time. It also is a

model that allows one to study the military worth of an element in the basis (i.e. what is the military value of more "information" in theater air defense?) without reference to a specific system. This "sheds light" on the importrnce of the element and all the systems whose major contribution is that element. It is a model that promotes learning about the importance of key interactions.

Credible/Agreeable/Useable

Since total force analysis cuts across many military organizational responsibilities, functions and disciplines, there is a real need to coordinate and get major agreement on the following:

- The model and its interactions
- Database for the model

The model also must afford a transparent, easily described structure to specify how military forces are deployed and employed. The end result is an "agreeable" analysis tool with many users.

However, to be "agreeable" (producing acceptibility of results) the model/analysis must be believable. This "credibility" of model analysis results is brought about by a verification process peculiar to operations analysis:

- A credible whole model is the sum of its credible parts and their interactions
- The model/analysis results and trends must make sense and cause/effect must be traceable
- Model results need to compare well with limited scope test results

The first, results from a model development whose origin begins with a thorough examination of the problem, its parts and potential interactions. The second, results from a good database, a model with sufficient/flexible output, and keen analysis of cause and effect. The last is a bonus, if one is fortunate to find a good documented test case.

And finally, to be "useable," the model must not be overburdened with unnecessary detail that requires one to gather a difficult database and that dictates very long computation time.

The TADENS-C^3 development process has been strongly guided by the above principals with much emphasis on the following:

- A thorough examination of the theater air defense problem/interactions and definition of a model with a "basis" of key interactions.
- Coordination on the model development with a broad spectrum of military/defense organizations involved in air defense.

The model is planned to be available Nov 80. Only time will tell if the model management process produces a result that is credible, agreeable and useable.

Theater Air Defense Problem

Problem Scope

The nature of theater air defense interactions and the questions being asked to be quantified, dictate the need for a theater level model with the following key interactions:

- Defensive counter air (DCA)/Offensive counter air (OCA) operations
- Coalition DCA/OCA over a broad geopraphical area (i.e. NATO Central Region)
- Environmental effects (terrain, weather, electronic counter measures, weapons effects)
- Interoperability of forces of diverse nature
- Explicit-procedural C^3/information
- Systems (surface to air missiles-SAM, short range air defense-SHORAD, anti-aircraft artillery-AAA, fighter interceptors-FI, identification friend and foe-IFF, navigation) and deployment
- Logistics of SAM/FI
- Identification/airspace control/fratricide
- Tactics/procedures/employment

TADENS-C^3 Model "Basis"

The TADENS-C^3 model is being designed to include the aforementioned broad "basis" of interactions to provide a model for learning. A basic one-sided "mirror image" of the force model is shown in Figure 2. The computer programming of the interactions is such that a given interaction can be taken out of the model, through input, and not pay the associated computational price if the interaction is not wanted or needed. The level of detail in an interaction is such to capture the essense of its effects yet keep model computation time to a minimum. As the model is used, and learning occurs on the importance of interactions, some interactions may be taken from the model input to improve computation time.

C^3 Model "Basis"

Figure 3 shows the "basis" of interactions included in the C^3 part of the model. Input is flexible to allow the analyst to build whatever C^3 system/network is needed. The following additional "basis" of interactions are defined and planned:

- Capacity of sensors, links, nodes
- Content and quality of information (messages) from sensors/units
- Terrain/ECM/kill interruptions
- Node level of command
- Link data/message restrictions
- Separate networks/fusion at common nodes

(Lynch, U.H.D., 1979) is the definition of changes to an existing model DADENS-C^2 that is currently planned to provide the framework for TADENS-C^3. A portion of this reference is provided as an appendix to this paper to provide the reader with a sample description of the level of detail defined for the "basis" of interactions in TADENS-C^3.

Quantifiable Tradeoffs

The following is a list of foreseeable, quantifiable tradeoffs inherent in the TADENS-C^3 "basis" of model interactions:

- Military worth of more C^3 versus more resource (i.e. SAM/FI)
- Military worth of more timely, accurate information on air defense
- Impact of ECM-resistant, interoperable IFF on identification
- Changes in FI fratricide under different (procedural vs close C^3) airspace control techniques
- Mix of FIs (mobile/flexible but C^3 and weather dependent) and SAMs (lethal, quick-reacting but not mobile)
- Key ground-air resource survivability (C^2 centers, AWACS, etc.)
- Impact of ground sensor netting for SHORADS
- Impact of ground sensor turnoff (increased survivability) with AWACS capability
- Interoperability of FI with base logistics in NATO
- Impact of not sensing real killers (bombers?) in a massive attack
- Point defense versus area defense
- C^3 system capacity/saturation effects
- Impact of holding SAM/FI resources in reserve for better force utilization over time
- Impact of satellite relay/navigation (more survivable?) on force effectiveness over time
- Stockpiles of weapons needed/use rate in a massive attack

Model/Development Status

Model Framework

The Divisional Air Defense Engagement Simulation-Command and Control (DADENS-C^2) is an existing model whose framework (75,000 lines of code, six modules-500,000 bytes largest module) is a candidate for the TADENS-C^3 model. As of July 1979, DADENS-C^2 is completely user documented, mathematically verified with four structured and documented test cases, and operating on an IBM 3032 computer. The model capabilities have been compared against the desired theater air defense "basis" of interactions and the required changes defined. A powerful model in its own right, DADENS-C^2 takes about three man-months to train an analyst to use and interpret. While TADENS-C^3 is in final development, DADENS-C^2 will be used to study specific problems for which it is credible. Documentation on the existing DADENS-C^2 model is at reference (BDM Corporation, 1979). Results of the test cases, and model "useability," is currently in analysis at the time of this paper. An evaluation of the DADENS-C^2 model and the defined changes will be

done by a broad spectrum of US military/defense organizations in early August 1979.

Tentative Schedule

Provided the DADENS-C^2 model is chosen as the model framework to modify, the TADENS-C^3 model capability should be available by November 1980. The decision point on DADENS-C^2 development is planned for August 1979. Current information on TADENS-C^3 development status will be verbally reported at paper presentation.

References

BDM Corporation/W-77-476-TR, Feb 1979, Sponsored by HQ USAF, ACS/SA
"Volume I DADENS-C^2 Executive Summary"
"Volume III DADENS-C^2 Planner's/User's Manual - Input Data"
"Volume IV DADENS-C^2 Functional Documentation"

Lynch, U.H.D., July 1979, "Theater Air Defense Engagement Simulation-Command/Control/Communications-TADENS-C^3 Change Definition," HQ USAF, ACS/SA.

Appendix

I DEFINITION OF ECM/ECCM INTERACTIONS

1. ECM Generators

a. Threat Types - Standoff jammers (SOJ), escort jammers (ESJ), and ground jammers (GDJ) will be modelled. The ECM threat will be attackable by Blue defense resources as follows:

ECM Threat / Defense	SOJ	ESJ	GDJ
SAM	X	X	
AAA	X	X	
Artillery (BM)			X
DCA FI	X	X	
Blue Strike	X		X
Blue OCA Cells	X		X

b. Defense (Blue) Types - Blue strike escort jammers, ground jammers and standoff jammers will be simulated in like manner as para 1.a. A capability will be added to designate a variable number of the 63 FI/SAM defenses in DADENS-C^2 as "Red." The Red defenses will interact with Blue strike/OCA aircraft in like manner as the "proposed" Blue defenses in TADENS-C^3. A portion of all current threat cells (types aircraft also) other than Blue strike, will have the capability of being identified in the input (and in the IDENT AIRSPACES) as a Blue OCA strike force.

As such, Blue ground jammers shall be targetable and vulnerable to all current Red threat types and vice versa. Blue SOJ shall be vulnerable to Red SAM/AAA and Red cells with an alternate mission to sense and attack Blue (non-reacting) SOJ (i.e. similar to Red KILLER threat to AWACS). Red defenses (i.e. SAM/C^3 network) shall have the capability to sense a Blue AWACS and attack. The converse shall be true for Blue Strike/OCA cells and SAMs against the Red AWACS.

2. ECM Equipment

All Red/Blue ECM threat types shall be capable of carrying the following types (in variable number) of ECM equipment:

ECM Carrier \ Equip	Noise Jam				Deception		
	Barrage	Spot	SSJ	Smart	Chaff	Flare	Electronic
SOJ	X	X					
ESJ	X	X		X	X	X	X
GDJ	X						
A/C Cell			X		X	X	X

Each ECM carrier shall have input to define several fixed time intervals to turn ECM equipment on/off. The noise jammers on carriers shall be modelled by standard jamming power/range equations constrained by coverage geometry defined relative to the carrier.

3. ECM Environment Generator Module

The time dynamic ECM carrier/equipment definition in para 1 and 2 shall be used to compute the ECM environment (i.e. jammer signal power in a variable frequency range) at any point in space. Terrain masking shall not be currently considered but near earth line of sight constraints shall be considered for ground jammers.

A precomputed (PEG like) ECM environment generator (fixed time interval) stored on disc/tape shall be examined as a means to save computation time for a specific threat/defense scenario. Knowledge of ECM generators killed, on/off, at a specific time can be used to compute the ECM environment at a specific spatial point. Since both Red and Blue ECM threats are considered, self jamming of Red/Blue defense will be inherent in the ECM Environment Generator Module.

4. ECM Effects

ECM impacts on Red/Blue defensive elements shall be:

A. Noise into radar antenna/IFF equipment/navigation

B. Jamming of communication links

C. Deception/degradation of radar information/quality

D. Degradation of launched weapons

a. Radars

(1) All ground surveillance radars shall be subject to impacts A and C. Consideration will be given to a means to model impact of A and C on the "simple" radar model for SAM/AAA units. All individual ground radiating targets shall have a capability/option(determined by input) to sense ARM attack and automatically turn off radar. An option shall be added to turn off/on individual radars at time intervals fixed at input.

(2) Air Surveillance

AWACS and satellite radars shall also be subject to impacts A and C. The ECM Module shall be constructed in a way that includes modelling jamming of individual FI radar (see para II3c5).

(3) ECCM

Command and control techniques/procedures shall be examined/modelled to simulate the capability of C^2 centers to triangulate or allocate a resource to fly down a strobe.

b. Communication Links

All ground/air communication links (explicit, implicit, or implied) shall be subject to impact B. The major effect will be a relationship between S/J ratio and message error (i.e. no information, partial information, message repeat).

c. IFF Equipment/Navigation

Several types of IFF equipment will be modelled to place on all defensive units. A match of IFF equipment shall be required for a potential correct IFF response. IFF on all aircraft shall have the capacity to turn on/off by prespecified input time intervals. IFF equipment on aircraft shall have defined interrogation geometry for a

potential correct IFF response as a function of interrogation capacity and ECM environment at sender and receiver. For navigation see para II2.

d. Weapon Effects

All weapons (SAM, AAA, BM, RPV, guided bombs, ASM, ARM, etc.) shall be subject to degradations (i.e. reduced CEP, SSKP, etc.) resulting from the ECM environment through which they must transverse.

5. Model Change Mechanization

As much as possible, all model change shall be made in a manner that the interaction can be eliminated through model input and not impact the model configuration/run time/efficiency.

II DEFINITION OF SENSOR/INFORMATION QUALITY CHANGES

1. Visual Model

An additional visual model will be added and capable of being attached to the following entities be they Blue or Red: SAM, AAA, DCA fighter interceptors, OCA aircraft. Ten (10) types of visual models will be capable of input, any one type which can be attached to a given resource entity. Two range inputs, for each entity (ground or air) capable of being acquired by the visual sensor, will define the model as follows:

Information at each range	Distribution	Default
"type" entity identification	uniform	perfect
number of entities	normal	perfect

If the entity, having the visual model, is in a weather airspace (see para III) of specified visibility range, this latter range will limit the visual model.

2. Navigation Site/Sensor Model

A navigation capability will be modelled which can be attached to any node of a C^3 network. The model will be a $1/R^2$ signal strength, line of sight transmission model constrained by azimuth/elevation limitations. There will be the capability to have up to five (5) types of navigation systems. The accuracy of the system will be modelled by normal distributions, on position and velocity accuracy of update, as a function of number of received signals. The node navigation capability shall be lost/damaged in the same manner as the node. Entities in the scenario shall be capable of receiving navigation updates provided they are characterized as follows:

- Entity has a receiver on board of the navigation system type.
- Signal strength required to receive a signal is available from the source. (Navigation link susceptibility to ECM jamming will be included in the model)
- Minimum number of received signals needed are available at the receiver.

3. Radar Models (all current types in model)

a. Information Quality

Physical acquisition of objects by radars will be modelled as currently done. However, the information content/quality at acquisition/during tracking will be a function of range. A variable number of ranges will be input for each radar type. At each input range, the following inputs will characterize the content and quality of the acquisition/tracking information:

Information Content	Quality/Distribution	Default
"type" entity identification	uniform	perfect
number of entities	normal	perfect
position of entities	normal	perfect
velocity vector	normal	perfect

"Type" information above will be added to the IDENTIFICATION airspace logic.

b. Low Level Clutter/Multipath

A separate volume shall be defined for each positioned radar in which acquisitions are degraded due to clutter/multipath. Acquisition information content/quality within this volume will be characterized by a different set of inputs as in para 3a.

c. Radar Model Capacity

1) Aircraft Types - A capability will be added to allow (or limit) a radar type to see any and all types of aircraft, which must finally be classified as HOSTILE/FRIEND/UNKNOWN in the C^3 network per logic of the IDENTIFICATION airspace.

2) Track Production Areas (TPA)

A fixed airspace (TPA) will be associated/attached to each radar. Though the radar may acquire objects outside the TPA, the radar does not send an acquisition message through the C^3 network unless the object is in the radar's TPA.

3) Track Capacity

An input will be added which limits the number of tracks that a radar can handle within its TPA. A saturation message will be sent to the PCC at the beginning of saturation and at its conclusion. Objects determined as FRIEND will be dropped from this capacity accounting.

4) Satellite/Sensors/Communications

Position of satellite/sensors shall be capable of input (latitude/ longitude or UTM) as a function of time. Communication links between satellites or to the ground shall be limited by LOS/Earth constraints. Current radar model and navigation sensor (see para 2) will be associated/carried by a specific satellite.

5) Aircraft Sensing (Radar) Model

In addition to the visual model (para 1), a radar model will be added to each aircraft type for acquisition. For each type entity which the radar can acquire, the following inputs will be possible: relative range at which entity is sensed; positive relative altitude limit; lower relative altitude limit. As such, a range and altitude check determines if the aircraft acquire an entity. No information other than the relative position of a potential target is to be implied by this acquisition. Degradation of the radar range by ECM will be modelled (see para I4a).

III WEATHER MODEL DEFINITION

A weather airspace (s) will be defined by centerline (two points), width and altitude band (two points) inputs. Within this airspace a visibility range will be modelled as a function of time and linearly interpolated. The visibility range in the airspace will limit the visual model of para II 1. Knowledge of weather at PCCs will be perfect information but delayed by a time interval defined by input.

IV COMMUNICATION NETWORK CHANGE DEFINITION

1. Communication Network

Links between nodes (senders/receivers) will be associated with a specific network name. Information on this network must be transmitted over links defined for this network. Multiple links, between nodes in a network, shall be limited (by input) to specific message "types/numbers." A flexible switching logic shall be constructed at a node having multiple links to another node. A node will have a capability for data "fusion" (by input) between different networks at the same node. Several communication link routing logics between sender and receiver (i.e. shortest time, minimum links) will be implemented.

2. Unit Status Information

Unit status information, which is used in the decision process of resource allocation through command and control, will be integrated into the information flow modelling of the model.

3. Links

A capability to disconnect/reconnect a communication link (i.e. at any point on a path from sender to receiver) based on time will be constructed in the model. Air to air and air to ground links will be LOS/Earth constrained (not terrain). Explicit jammable links will be defined to and from aircraft within the C^3 network.

4. Command and Control Centers

a. Message "type" priority for processing will be defined by input for each C^2 center. Because TPAs (see para II3c2) may overlap or because a C^2 center may receive several tracks (of different quality) on a single threat, a track correlation (uniform distribution on perfect track correlation knowledge) model will be implemented. On those tracks which do correlate, a "track quality" model/decision process will be employed. A workload/capacity model will be constructed for the C^2 center decision process.

b. Tactical Network Control

If a radar below the PCC has been destroyed (assume perfect information), the PCC shall have the capability to assign the TPA of the destroyed radar to another radar in its network (i.e. assign alternate TPAs to radars at input) after a fixed decision delay time. A PCC in a DEFENSE shall be limited to control specific resource types/locations defined by data input. PCCs at a lower level in the C^3 network will send messages to a PCC at higher level on force allocation to targets. The PCC at the higher level will send messages to control/interrupt the resource allocation of the lower PCC based on the information it has available. New command and control messages will be defined (see para VII) for a high level PCC which will be limited to flow over specific links (see para IV 1) to lower level PCCs.

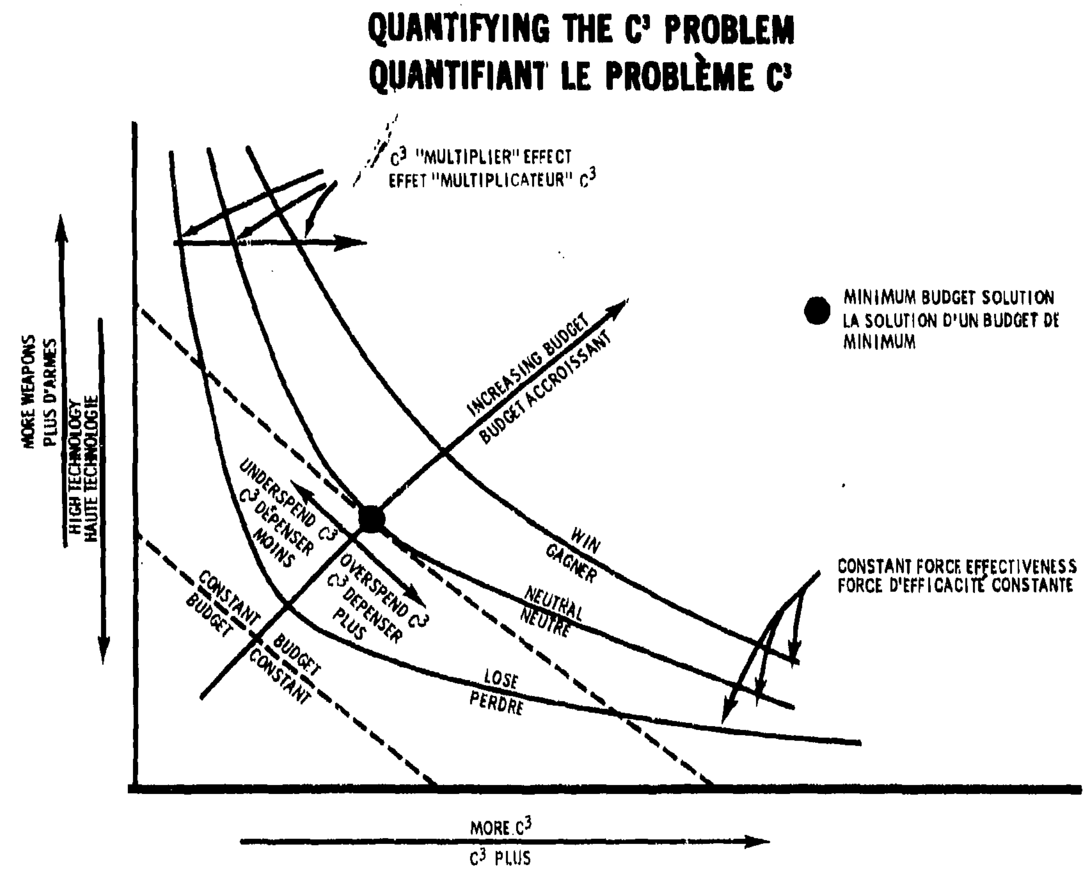

QUANTIFYING THE C³ PROBLEM
QUANTIFIANT LE PROBLÈME C³
C3 "MULTIPLIER" EFFECT
EFFET "MULTIPLICATEUR" C3
MORE WEAPONS
PLUS D'ARMES
HIGH TECHNOLOGY
HAUTE TECHNOLOGIE
MINIMUM BUDGET SOLUTION
LA SOLUTION D'UN BUDGET DE MINIMUM
INCREASING BUDGET
BUDGET ACCROISSANT
UNDERSPEND C3
C3 DÉPENSER MOINS
OVERSPEND C3
C3 DÉPENSER PLUS
WIN
GAGNER
NEUTRAL
NEUTRE
LOSE
PERDRE
CONSTANT BUDGET
BUDGET CONSTANT
CONSTANT FORCE EFFECTIVENESS
FORCE D'EFFICACITÉ CONSTANTE
MORE C3
C3 PLUS

Figure 1

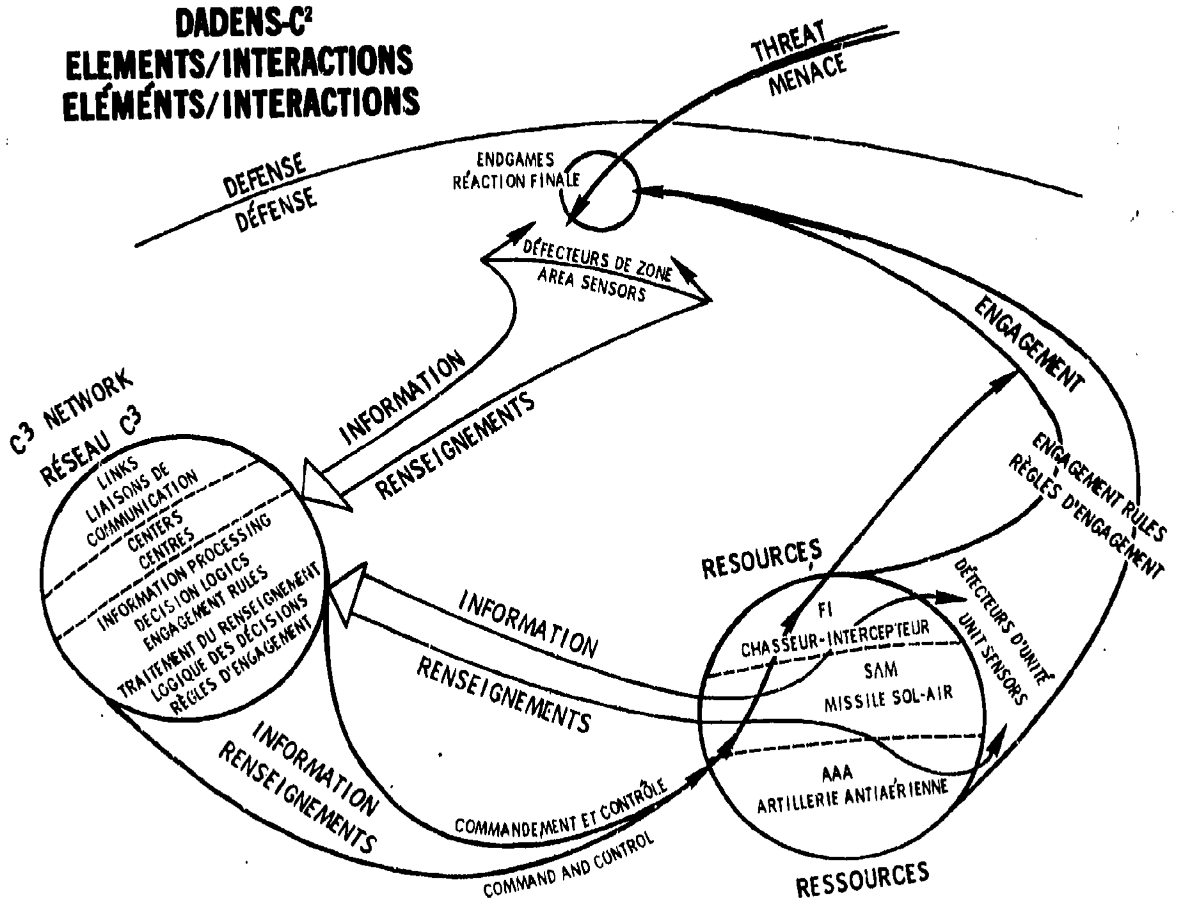

DADENS-C²
ELEMENTS/INTERACTIONS
ELÉMENTS/INTERACTIONS
THREAT
MENACE
DEFENSE
DÉFENSE
ENDGAMES
RÉACTION FINALE
DÉFECTEURS DE ZONE
AREA SENSORS
INFORMATION
RENSEIGNEMENTS
ENGAGEMENT
C3 NETWORK
RÉSEAU C3
LINKS
LIAISONS DE COMMUNICATION
CENTERS
CENTRES
INFORMATION PROCESSING
DECISION LOGICS
ENGAGEMENT RULES
TRAITEMENT DU RENSEIGNEMENT
LOGIQUE DES DÉCISIONS
RÈGLES D'ENGAGEMENT
ENGAGEMENT RULES
RÈGLES D'ENGAGEMENT
RESOURCES
DÉTECTEURS D'UNITÉ
UNIT SENSORS
INFORMATION
RENSEIGNEMENTS
FI
CHASSEUR-INTERCEPTEUR
SAM
MISSILE SOL-AIR
AAA
ARTILLERIE ANTIAÉRIENNE
INFORMATION
RENSEIGNEMENTS
COMMANDEMENT ET CONTRÔLE
COMMAND AND CONTROL
RESSOURCES

Figure 2

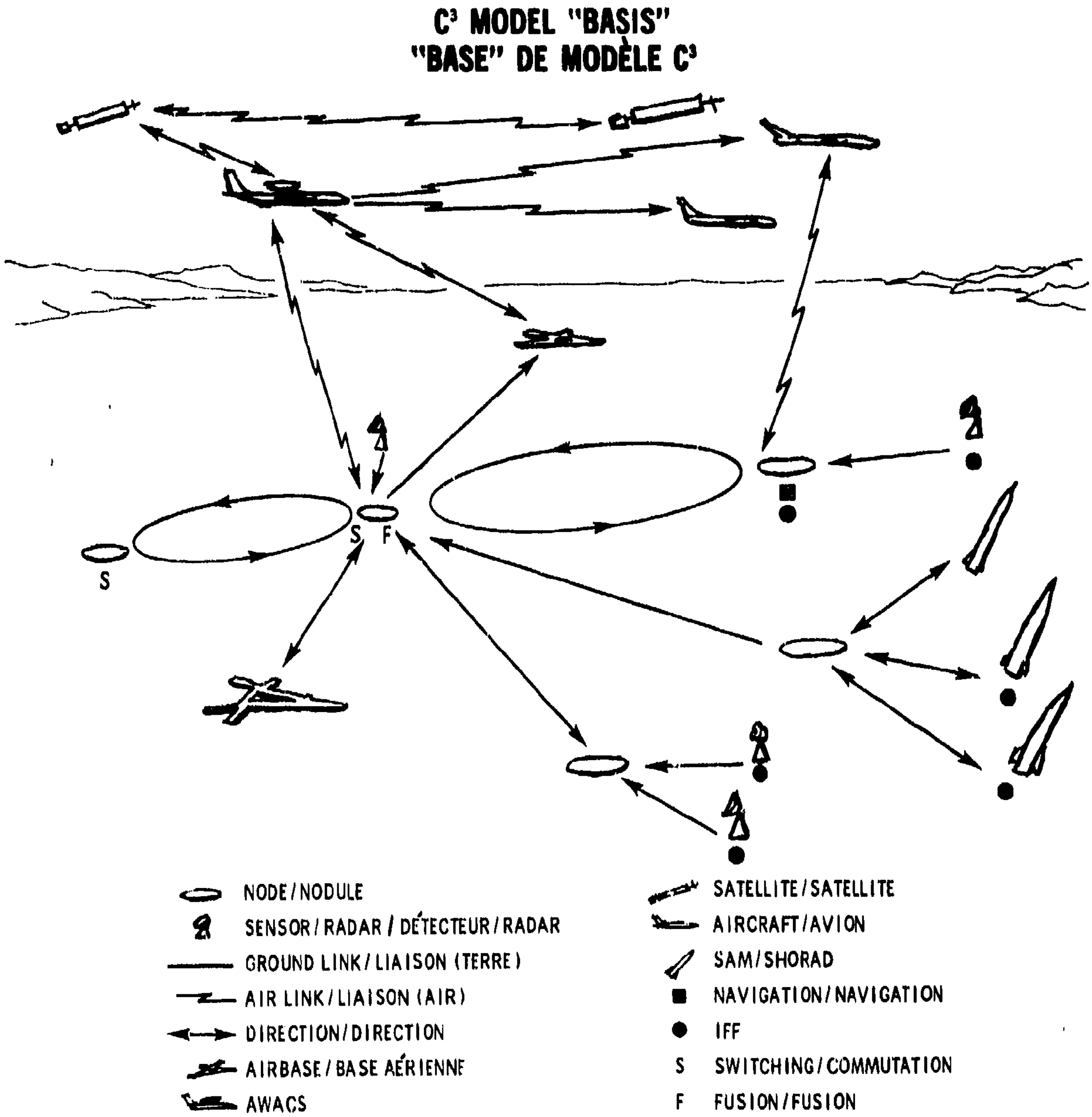

C³ MODEL "BASIS"
"BASE" DE MODÈLE C³
S
S F
NODE/NODULE
SENSOR/RADAR/DÉTECTEUR/RADAR
GROUND LINK/LIAISON (TERRE)
AIR LINK/LIAISON (AIR)
DIRECTION/DIRECTION
AIRBASE/BASE AÉRIENNE
AWACS
SATELLITE/SATELLITE
AIRCRAFT/AVION
SAM/SHORAD
NAVIGATION/NAVIGATION
IFF
S SWITCHING/COMMUTATION
F FUSION/FUSION

Figure 3

SIMULATION OF AIR DEFENCE OPERATIONS AND MULTIPLE AIR COMBAT

H.R. Wilhelm
SHAPE Technical Centre
P.O. Box 174
The Hague
Netherlands

SUMMARY

This paper describes the air defence system simulation model in use at the SHAPE Technical Centre. The model comprises detailed submodels for airborne and ground-based early warning sensors, command and control operations, ground-controlled intercepts, multiple air combat engagements, and electronic countermeasure operations. Modifications in hand will include the simulation of surface-to-air missile systems and will permit the interactive running of the model as a one-sided wargaming system with a battle manager commanding and controlling his air defence force via graphics displays. The computer configuration used in running the model is described and also the specific software methods employed. A three-dimensional graphics facility was developed to facilitate the evolution and validation of tactics for modern fighter aircraft and future missiles. Additional validation methods were applied, such as the correlation of model results with live flying trials. The paper closes with a brief account of past and possible future applications.

1. INTRODUCTION

In 1975 the SHAPE Technical Centre, The Hague, Netherlands, initiated the development of a theatre-level model for the simulation of integrated air defence operations. At that time it was realised that the operations analysis community in general and SHAPE Technical Centre in particular were lacking the tools for the credible assessment of the operational performance of air defence systems. An air defence system may be considered as being composed of several subsystems:

- An air surveillance subsystem
- An air resource allocation subsystem
- A weapon control subsystem
- A communications subsystem
- Weapons systems.

In reality, the first four components are combined into the "Air Command, Control and Communication System".

The air defence system is extremely complex, with many interactions between its subsystems at various levels of command. Because of this and because of the lack of experience in the design and validation of a model describing such a large system, it was decided that the process of developing the model should be split into several phases and that the scope of each phase should be dependent on the experience gained in previous phases. As a result model development is a time-consuming evolutionary process extending over several years and interrupted by production periods when the evolving model is in use.

The first phase in model development was concerned with establishing a framework and structure for the complete model with some parts being fully implemented. The product of the first phase of development is the "COMO Interceptor Operations Model". Particular emphasis was placed on the final stage of the intercept process, the interactions between groups of opposing aircraft, as it was determined that statements on the factors affecting the outcome of air combats were virtually unsupported by hard facts or credible analyses and were mainly governed by subjective and very often contradicting personal opinions of fighter pilots. It was felt that the effectiveness of air defence systems could be determined only if the final stage could be represented credibly.

It was decided to implement the detailed engagement tactics of m versus n aircraft because only one-versus-one simulation programs and simulators were available and this appeared to be completely unrealistic since no air force in the world would send one fighter on a mission. There were no means for extrapolating from the results of one-versus-one simulations to those of many-versus-many.

This paper is split into five parts: the first part contains a description of the current operational status of the interceptor model, the second and third parts give an outline of the computational techniques used, the fourth part is concerned with the validation methods, and the fifth and final part deals with the modifications in hand to convert the interceptor operations model into an air defence system simulation model.

2. THE COMO INTERCEPTOR OPERATIONS MODEL

2.1. Description

The COMO Interceptor Operations Model is a theatre-level air combat model for the simulation of the ground and air operations of a force of air defence fighters against multiple raids. The model design was a co-operative effort of the General Research Corporation, Huntsville, and the SHAPE Technical Centre, The Hague. The model includes simulations of the functions of:

- Ground-based and airborne early warning sensors
- Command and control
- Airbase operations
- Ground-controlled intercept mission profiles
- Airborne target detection, acquisition, and selection
- Airborne missile launch computer

- The human decision-making process of selecting aircraft manoeuvers
- Aircraft manoeuvers
- Missile lock-on
- Missile launch and fly-out
- Missile end game effectiveness function.

The conceptual model structure of the defending side is shown in Figure 1. The defence elements consist of airborne and ground-based sensors, track files, and airbases linked to one of several possible Command and Control Centres; fighters are linked to their respective airbases and each fighter can carry one or two types of missiles.

The conceptual model structure of the attacking side is indicated in Figure 2. Medium bombers, fighter bombers, escort fighters, self-screening jammers, escort jammers and stand-off jammers may be the elements of an attacking formation. Escort fighters and self-screening jammers may carry one or two missile types.

Figure 3 indicates the sequence of modelled events. A typical example of the events simulated is:

- Formations penetrate into an area to be defended
- They may or may not be detected by early warning sensors
- Tracks are built up on targets detected and resolved
- Interceptors are allocated and dispatched against the threat
- Interceptors fly on a GCI course and search for targets
- Upon target detection the interceptors try to manoeuver themselves into firing position and deliver air-to-air weapons
- After missile launch the interceptors may engage other targets or return to base if their fuel or missile stock is depleted
- Attacking aircraft search for interceptors
- Upon detection of interceptors, fighter bombers run away and escort aircraft engage in air combat by trying to manoeuver themselves into position to deliver air-to-air missiles.

The features modelled are elaborated in the following paragraphs.

Sensors report plot information on detected targets to the Command and Control Centre, which is supposed to represent the combined intelligence and computer power of the Ground Environment System. In reality, the task performed by our single Command and Control Centre would be performed at different levels of command and at different locations. For the simulation program, however, this does not make any difference, except for the time delays which are represented in the model.

The Command and Control Centre correlates the plot information with tracked targets and uses it to update target tracks and to build up new target tracks if the plots do not correlate with any tracks already available. In the book-keeping for a suite of track files a target count is performed, the count depending on the resolution capability of the sensor in question. Tracking errors resulting from system parameters and target behaviour may be superimposed, as well as any electronic countermeasures affecting the sensors. The effects of triangulation of targets in heavy ECM conditions can be simulated, but the well-known deghosting problem is assumed to have been solved. There is no deghosting algorithm in the program, and there are no tracks built up on ghost targets.

After target tracks have been established, the Command and Control Centre allocates air resources by comparing available fighters on airbases and on combat-air-patrol (CAP) patterns with hostile tracks. Fighters are allocated according to specified criteria, for example, to attempt to minimise enemy penetration, to attempt to maximise aircraft range, and to achieve a desired force ratio against targets counted. Due to erroneous target counts caused by limited sensor resolution or ECM it may happen that an insufficient number of fighters is allocated against the threat with the possible consequences of low effectiveness and a high loss rate.

If, on the other hand, the number of fighters allocated is more than sufficient, the defending side may prove to have allocated a significant proportion of its whole fighter force against a few targets, and does not have enough resources left to counter a second or third raid penetrating possibly some time later.

This brief and over-simplified account of some of the difficulties associated with intelligent resource allocation of fighters against the air threat makes it clear that this is a problem of enormous complexity which is very difficult to solve by "canning" resource allocation policies into an algorithm. It is in this area that the intelligence, pattern recognition capability, and intuition of a real-world battle manager comes into play. Therefore it is only logical that the next version of the interceptor model should be run interactively with a man-in-the-loop to take care of the resource allocation on the basis of information on the air picture and the resources available, presented to him by graphics displays.

Now, independently of how good or how bad the selected resource allocation policy may be, the Command and Control Centre eventually decides on the numbers and locations of fighters to be deployed and passes its orders to fighters already airborne (for example, circling in CAP patterns) or to airbases which, after a given scrambling time delay, launch the desired number of aircraft, provided the aircraft are available. The aircraft fly in formations assumed immediately after take-off.

The Command and Control Centre guides the interceptor formations to the desired kill point according to a specified GCI mode, which may be:

- Close control
- Loose control
- Broadcast control.

The attack tactics to be used are strongly dependent on the weapons carried by each of the participants. Tactics incorporated in the model include:

- Cut-off tactic (for all-aspect weapons)
- Final turn lead collision course (for rear hemisphere infrared weapons)
- Pursuit course (for example against targets being triangulated)
- Single turn tactic with a predefined track-crossing angle.

Interceptors search for targets using airborne detection devices such as A/I radar, FLIR, TV, or the human eyeball. The performance of the sensors is represented by detection ranges, single scan probability of detection, detection cones, or scan time. All the variables can be made dependent on weather conditions, ECM conditions, speeds, altitudes, and other system-dependent or target-dependent variables. After target detection, a fighter becomes autonomous and there is no link to the Command and Control Centre. The fighter is now "in air combat". Each aircraft in air combat passes iteratively through an air combat decision and manoeuvering logic at a fixed time step. The air combat decision and manoeuvering logic comprises:

- A target search and detection logic
- A target selection logic
- A manoeuver selection logic
- A missile in-range computation
- A missile launch logic
- A missile fly-out model
- A logic which implements the manoeuver selected and performs all integrations and updating of all aircraft and missile state vectors.

The target selection logic: Each fighter selects one of several detected targets, depending on specified criteria, and continuously updates this selection, switching over to a "better" target if there is one. Such a selection could be based on an estimated time-to-kill and time-to-be-killed with respect to each detected target, and the target chosen is that for which one of these is a minimum. Another basis for selection could be geometrical properties such as distance and look angle, from which measures of position of advantage or disadvantage could be derived for the possible targets.

All these logics have one fault in common: they assume perfect knowledge of each of several possible targets. Another assumption is that a pilot would be capable of assessing the value of and the danger represented by each of several detectable opponents and would finally choose the "best" opponent as his target. It is well-known that the number of "channels" in which a human operator can think is limited. Additionally, the time available to perform such an assessment is extremely short. Thus it seems unlikely that a pilot would really select the "best" target. This consideration immediately leads to the assumption of a random target selection logic. A reasonable target selection logic probably lies somewhere between the two extremes.

There does not seem to be a way out of the dilemma, because of the difficulty of modelling human behaviour and decision making under conditions of very high physical and mental stress. For obvious reasons, there cannot be a single "correct" target selection logic.

In this situation we took the usual operational analysis approach of trial and error. We made a sensitivity analysis, and implemented and tested different target selection logics. Fortunately, the overall results indicated that - although different logics resulted in more or less different absolute results of single simulated air combats - the trends extracted from a large number of simulation runs tend to be independent of the logic chosen and other factors such as force ratio, formation build up, missile performance, and IFF situation seem to be of higher importance than an "optimum" target selection which is in any way uncertain.

The combat manoeuver logic: The combat manoeuver logic implemented is comparable to the equivalent parts of well-known and well-reputed one-versus-one models. Depending on relative geometry and weapon performance, one of a suite of offensive or defensive manoeuvers is selected against the current target. Due to the target selection logic implemented, target switching may occur during a specific manoeuver. In this case the manoeuver is interrupted and another manoeuver is initiated against the new target.

In addition, specific tactics for the delivery of medium range air-to-air missiles were implemented at the request of a NATO Working Group. These tactics include:

- The extension tactic for delivering medium range semi-active missiles
- Stand-off tactics for delivering fire-and-forget missiles.

The missile in-range computation: At regular time intervals the program checks the firing opportunities for each aircraft in the game. A missile may be fired if all the following conditions are fulfilled concurrently:

- Seeker head is locked-on to the target
- Look angle to target is smaller than the off-boresight capability of the missile
- Target is within kinematic range
- Turning rate of line-of-sight is smaller than the maximum slew rate of the seeker head
- Target has been identified as being hostile.

Seeker head lock-on range may be described as a function of system-dependent and target-dependent parameters, for example, thrust setting, speed, altitude, and aspect angle for an infrared seeker head, or radar cross section, which may be dependent on the aspect angle for radar seeker heads.

A simple method of identification is simulated: an aircraft is considered to be identified if any other of

its opponent aircraft manages to close in to a distance smaller than the identification range specified. In this way, cooperative tactics for visual identification can be simulated: the first fighter identifies, the second fighter shoots. Alternatively, the identification range may be replaced by a set of curves of probabilities of identification as a function of distance to target. The kinematic range of a missile is input as a table dependent on parameters such as aspect angle, speeds, altitudes, or as a subroutine containing the software of an actual missile launch computer - if that information is available and releasable.

The missile launch logic: If all the necessary conditions are fulfilled a missile or a salvo of missiles can be fired against the target. The missile launch logic generates the missiles after a given time delay and takes care of any appropriate book-keeping such as a reduction in the number of missiles an aircraft carries or reductions in the mass and drag of an aircraft.

The missile fly-out model: The fly-out of each individual missile is simulated to a degree of detail not usually encountered in this type of model. The essential aerodynamic properties and control limitations are reasonably well represented. As the missile passes the target at close distance a Monte Carlo decision on the target kill is made on the basis of the missile kill probability, which may be a function of end game parameters such as relative speeds and track crossing angles. If a target is killed it is removed from the game, and surviving aircraft continue searching and attacking new targets until their fuel or missile stock is depleted. In this case aircraft re-link themselves to the Command and Control Centre, which takes care of their recovery and guides them to their home base. After landing on the home base, aircraft are put into a queue for reloading and refueling, and are available for new missions after a given time delay. Airbase operations are essentially modelled as serving the queues of aircraft to be repaired on the base, to be reloaded and refueled, and to take off. The appropriate stocks of weapons and fuel are reduced as aircraft are serviced. The sortie generation capability of the airbase can be made a function of the damage level of the airbase, which again may be a function of the number of bombers passing over the airbase during the game. Airbase attack and airbase vulnerability are not, however, explicitly modelled.

Attacking side: The attacking side is described in a simpler way than the defending side because the ground environment and airbase operations are not simulated. Attacking aircraft fly in formations of up to 31 aircraft. These formations follow a specified track, leading to the target to be attacked and returning to a "go home" point.

Attacking aircraft search for interceptors using their on-board detection devices such as A/I radar, FLIR, or the human eyeball. If an interceptor is detected, escorting fighters accept the engagement and start to close in and attack. The air combat logics for escort fighters are identical to those for interceptors. Escorts try to manoeuver themselves into firing position and launch missiles if they can. The missile fly-out is simulated and a Monte Carlo decision on the effect of a "missile explode" event is made.

Fighter bombers try to avoid engagement by interceptors by running away if an interceptor manages to come closer than a critical distance. If the interceptor still continues closing in, fighter bombers drop their weapon load and try to avoid being shot down by performing evasive manoeuvers.

Medium bombers are non-responsive to any attack by interceptors: they continue flying on their predefined track and are easy targets for interceptors which manage to break through the screen of escorting fighters.

If escort fighters or fighter bombers survive to be engaged by interceptors they continue flying to their next trackpoint or return home if their fuel stock drops below a critical value.

Elements of each formation may be defined as jammers. There are provisions for three types of jammer:

- Escort jammers (ESJ)
- Self-screening jammers (SSJ)
- Stand-off jammers (SOJ).

The effects of ESJ and SSJ are modelled primarily by denying the ground environment the capability of counting the number of targets flying within a formation. The engagement of a jamming formation is initiated only if the formation is detected by at least two sensors so that strobe triangulation is possible. Additionally, detection ranges and kill probabilities can be made a function of jamming. The aggregate effects of all jammers in the game for each sensor are determined for the current line of sight, so that specific sectors of sensors degrade and black out dynamically during the game. Burn-through and sidelobe jamming are neglected.

2.2 Input Data Required to Drive the Program

Input data are required to describe:

- The scenario
- The function and performance of the Command and Control System
- The aircraft performance
- The missile performance.

All data are input by a special free-format input language (COMIL), which is very fast and flexible and allows the definition of scenario, tactics, and performance to almost any degree of detail. The input file drives the program.

The scenario is described by a set of data defining attack routes and threat formation build up. Several aircraft types in different numbers can fly in the same formation, and the performance of each of the aircraft types has to be defined separately. Early warning sensors have to be defined with respect to their position, detection capability, and terrain screening. The tracking capability of the system has to be described by maximum number of track files, time delays, and tracking errors. Allocation rules resulting

in policy or strategic decisions are defined for the Command and Control System. Airbases are defined with respect to their position and aircraft servicing and sortie generation capability. Different interceptor aircraft types may be deployed on different airbases. Some aircraft may be airborne and circling in combat air patrol patterns at the start of the game. Aircraft performance is described by means of drag and lift co-efficients and thrust as a function of Mach, altitude, thrust setting, wing sweep and so on. Initial fuel load and specific fuel consumption as a function of different flight parameters have to be defined. Each aircraft may carry up to two air-to-air missile types, the performance of which is defined by the acquisition performance of the seeker head as a function of system-dependent and target-dependent parameters, thrust profile, drag characteristics, lateral acceleration capability, and end game effectiveness. A medium size scenario with a few attacking formations, several sensors, airbases and interceptor types may require between some hundreds and some thousands of input values to be defined, depending on the degree of detail desired and the level of aggregation being played.

3. HARDWARE CONFIGURATION FOR RUNNING THE MODEL

The computer configuration is shown in Figure 4. The model resides in memory in the CDC CYBER 173 computer. A graphics terminal is connected to the CYBER 173. During execution of the model the position of all participating combat units is displayed on the screen of the graphics terminal at chosen time intervals (for example, every ten game seconds the positions of the combat units are displayed). The user can monitor the progress of the game and control the running of the model.

A set of output commands enables the following information to be stored on disc or given as listed output of the running simulation:

(1) History of the game. The history contains X-Y locations, height, speed components, acceleration components and variables of which the value changes in the course of the game, e.g., fuel on board, number of missiles available, number of missiles fired, name of the target.

(2) Results of the simulation run. Contents are: name of an aircraft which launched a missile, name of the target, name and type of the missile, speeds of the launching aircraft and the target, look angles, closing speed and thrust levels at time of launch, etc. The results include the outcome of a "missile explode" event, indicating whether it was a target kill and if not what was the reason.

(3) Debugging and testing aids. They contain memory dumps, check listings and maps.

Output stored on disc can be post-processed and statistical analyses with plotted information may be made automatically or controlled through an output control terminal.

Another command forces the running model to write history-like information on a magnetic tape. This tape can be processed and run by STC's graphics facility to give a detailed view of the game on a large-screen three-dimensional graphics display similar to a moving picture. Additionally, the graphics facility can be driven by the CDC computer.

Example output generated by the model control graphics terminal is presented in Figures 5 - 7 which show a sequence of three hardcopies taken from the terminal at several game-minute intervals. This run simulated an attack by approximately 150 aircraft at low altitude in close formation; the aircraft diverted to various air defence installations in TWOATAF. Airborne early warning was provided by an E-3A aircraft circling over the Netherlands. Fifteen CAP patterns with a manning of two aircraft each were deployed over the area. Aircraft positions are displayed every ten seconds. The information which can be extracted from these hardcopies is limited but they illustrate the capability of the model to handle theatre-level analysis and still simulate each sensor, aircraft, and missile to almost any desired degree of detail.

4. SOFTWARE TECHNIQUES USED

The COMO simulation system was used for the implementation of the interceptor model because of its highly flexible and efficient input and computer resource management system. COMO is a combat simulation system developed by the SHAPE Technical Centre and is a tool for the generation of critical-event combat simulation models.

The framework of the COMO simulation system includes the features which are common to all simulations of this type. These features include book-keeping, sorting, scheduling, and provision of functions which are frequently used in combat simulations, such as searching for targets, weighting of detected targets, calculation of relative speeds and geometry, and so on. Thus, the designer of a combat simulation program does not need to implement these common features each time he writes a simulation program. He can concentrate on the essential features of the weapon systems simulated provided he ensures that the interface between the weapon system simulated and the COMO frame functions as designed. The routines describing a weapons system must be written in FORTRAN, according to specific rules which permit the weapons deck routines to be read in as input and processed by a run file assembly processor. The processor generates the code that has to be added to the COMO frame to give a complete simulation program. This rather complicated process of generating a simulation program is fully automated, and the designer of the program has merely to insure that his weapons system description conforms to the conventions. This process is shown in Figure 8.

Although COMO has been divided into several overlays to save storage, a medium-size weapon deck and a scenario with a few hundred combat units participating simultaneously in the game would require a computer with a memory size well above 150K memory locations. It was recognised early in the development of the COMO program that the vast amount of input data required to define a scenario and the variables required to describe, update, and integrate the changing properties of combat units participating in the game

would occupy a large proportion of the memory available and would limit the simulation capability of the software system.

An example may illustrate this problem: assume that one of the changing variables describing a combat unit, say, an aircraft, is a flag which is set if this aircraft is attacking a target and reset if the aircraft is no longer attacking a target. This flag is a switch which can be represented by one single bit. In normal FORTRAN coding the flag would require one single word of memory comprising 60 bits (for a CDC computer). This is a memory utilisation of only 1.7%.

To keep storage requirements within reasonable limits, an extensive pack and unpack facility was included in the COMO simulation system and this facility resulted in a significant reduction of memory requirements. Input data and data changing during the game are stored (packed) several items per word, according to certain packing rules which have to be defined for every variable. The unpack procedure extracts items according to the same rules.

Packing and unpacking adds to the overhead of the simulation program and of course requires run time. To keep the additional run time to a minimum, pack and unpack routines are written in Assembly Code, and are optimised for minimum overhead.

An example taken from the COMO interceptor model illustrates the reduction in memory requirement when packing and unpacking is used as compared to conventional storing of data items in arrays.

In the interceptor model an aircraft is described by 53 data items which may change during the game. These 53 data items are packed into 8 words. In normal FORTRAN coding 53 items require 53 words.

The advantage of packing is reduced by the overhead required for packing routines. Figure 9 shows a comparison of the memory size required for storing the 53 changing properties of an aircraft as simulated in the interceptor model for normal FORTRAN coding and for packing in COMO, as a function of the number of combat units in the game. A bias of 2200 words for packing overhead is taken into account. It is assumed that all the FORTRAN coding would be done as efficiently as in the COMO system. Figure 9 shows that packing/unpacking becomes economic if there are more than 55 aircraft involved in an air combat simulation.

5. VALIDATION OF THE MODEL

Validation of such a complex model is extremely difficult and has to be split into several parts:

(1) Debugging of the program
(2) Validation of the submodels which describe automatic systems
(3) Validation of the submodels which describe systems with human interaction
(4) Validation of the complete model with all submodels playing together dynamically.

5.1. Debugging

The debugging of the program is an obvious but non-trivial job. The task of debugging is to ensure that the program behaves as intended by the designers of the program. All the usual debugging methods have been applied to the program and the designers of the program are quite confident that the program is mature. However, it has been argued in the literature that there is no way of proving that a non-trivial program is totally bug-free. Consequently, we cannot prove that there is no bug hidden in the program.

5.2. Validation of Submodels Describing Automatic Systems

The validation of submodels describing automatic systems is a relatively easy task. The response of the modelled system is compared with that derived from real-life measurements or from detailed models that have already been validated. The following subsystem models have been validated:

- Sensor operations
- Track build-up and maintenance
- Airbase operations
- A/I radar detection
- Aircraft mission profiles
- Aircraft response on manoeuvers initiated
- Missile in-range computation
- Missile fly-out.

Additionally, the function of visual detection and identification was validated in that manner.

5.3 Validation of Submodels Describing Systems Involving Human Interaction

The validation of submodels describing systems with human interaction is a far more difficult job. Human decision making varies for each individual and there is no way of establishing a single "correct" algorithm describing human response. Nevertheless, human decision making has to be simulated in the type of model we are describing here and the best we can achieve is a "reasonable" algorithm found by trial and error.

The areas in which human decision making becomes very critical in an air defence system are:

- The air resource alloaction
- The airborne target selection and air combat manoeuvering.

When air resource allocation algorithms were tested it was found that the consistent application of the

algorithms to minimise target penetration may lead to engagements of low effectiveness and to high attrition rates because of lack of coordination in the timing of the withdrawal of interceptors from different combat air patrol patterns or the scrambling of aircraft from different airbases. This absence of coordination means that single interceptors or single pairs of interceptors sequentially engage a numerically superior threat, with disastrous results. Obviously, a mass attack should be countered by a mass defence.

As the tests show the low effectiveness of a possible air resource allocation subsystem the next step is to consider the manual override capability. Very little is known about how a military battle manager would allocate limited resources in the presence of uncertainty. The only way to find out is to make experiments with the man-in-the-loop, and this is in fact the main step in the model and facility development described in the final part of this paper.

The problems of airborne target selection and air combat manoeuver selection were discussed earlier. The implementation of reasonable algorithms was performed by model design and validation with support provided by experienced weapon operators.

A comprehensive pseudo-three-dimensional graphics package was developed at STC which made it possible to view a simulated air combat as a moving picture from any point in space including the cockpit of any aircraft involved in the combat. In this way, experienced pilots were exposed to the display of simulated air combats and, based on their comments, the algorithms and tactics were modified until a satisfactory state of model development was reached. Several iterations of this process were made. The graphics display system was used as a communications link between fighter pilots, the computer, the model designers and so served as a model design tool. Examples of hardcopies taken from the display are given in Figures 10 - 24.

5.4. Validation of the Complete Model

The validation of the complete model has not yet proved possible because of our lack of knowledge of human decision making with respect to resource allocation. It was possible, however, to validate a major part of the model by a comparison of its response with data collected during a major US flying trial. Output produced by the multiple air combat part of the model, including submodels for airborne detection and identification, target selection, manoeuvering, missile launch, missile fly-out and missile end game effectiveness, was compared with statistical data obtained from a major US live flying trial. The correlation was excellent.

However, even excellent correlation is no proof that the model is "correct". It is merely an indication that the model response is "reasonable" and that this part of the model is mature enough to be used for production runs.

6. FURTHER DEVELOPMENTS OF THE COMO INTERCEPTOR MODEL

The COMO interceptor model has been used intensively during the last two years - approximately 8000 air combat simulations were performed in total - and the main strong and weak points have been identified. As a result of this experience, we decided to split future development into two directions:

(1) Higher degree of detail and more resolution at the expense of computer resource requirements
(2) Higher degree of aggregation at the expense of resolution.

The more detailed model will be a development of the multiple air combat part of the interceptor model. It will be tailored to study weapon systems effectiveness and new tactics adapted to new weapons systems.

The more highly aggregated model will be tailored to reduce the weak points identified in our current air defence system simulation capability. As explained before, the weaknesses identified are not necessarily model deficiencies, but are due to our lack of knowledge of the behaviour of the individual human elements of the Command and Control System. The extensions being developed should give SHAPE and ourselves a better understanding of some of the operational problems, especially in relation to the human engineering aspects encountered in current and future Command and Control Systems. The program and model structure will be left unchanged: it has proven its flexibility and capability. Some modules, however, will be modified and simplified and new modules will be added.

As the current model is extended to simulate a real air defence system, the ground-based air defence will be included by the incorporation of medium-range and long-range surface-to-air missile systems such as NIKE, IHAWK, and PATRIOT.

Low-altitude short-range air defences (SHORADs) which include guns and short-range SAMs such as ROLAND and CHAPARRAL will be described at the appropriate level of aggregation.

IFF will be simulated as realistically as possible and fratricide will be simulated for cases of erroneous identification. The very detailed model of the manoeuvering of each individual aircraft and missile in close combat is hoped to be replaced by a more aggregate model designed by the Institute for Defence Analyses, US.

ECM simulation will be further improved and will also be applied against communications links, resulting in increased transmission time or loss of message, depending on the signal/jamming ratio of the current link-jammer geometry.

For low-altitude attacks, the effects of terrain line-of-sight interruption may be important. A terrain preprocessor will be used to compute visibility patterns for each individual sensor in the game by direct access of digitized terrain data.

Decision logics for implementing strategies will be based on algorithms similar to those already implemented or subject to manual override by graphical input/output. As the game progresses decisions will be based on available information and available communication links. In the interactive version, available and confused information will be presented at runtime in the form of an air picture at a graphics display and one or more alphanumeric displays will provide information on the status of the defence force. Decisions on resource allocation will be made on the basis of information available to a battle manager sitting in front of a screen and controlling his forces. The whole system will be set up as a one-sided wargaming system where one battle manager controls his own forces in the best way he can to defeat an attacker with a predefined strategy which is, however, unknown to him.

This wargaming version of the air defence system simulation will be yet another development phase and experience gained in this phase is expected to lead to a better understanding of reasonable strategy and resource allocation algorithms, and possibly to the design of better algorithms.

The most valuable application of the wargaming model might be the study of man-machine interfaces in Command and Control Systems by the measurement of the performance of different battle managers when playing with different options of command and control systems.

7. FINAL REMARKS

A model possessing unusual flexibility and growth potential was established at SHAPE Technical Centre. This model contains as a submodel the first operational multiple air combat simulation model available within NATO. The program has been used during the last two years to study the combat effectiveness of a set of current and possible future air-to-air missile systems and associated tactics. The main operational and technical factors determining the outcome of air combats were identified and measures recommended which would - when adopted - alleviate some of the major problems associated with airborne air defence operations in Allied Command Europe.

The experience gained during the last few years emphasises the relevance of the human element with its unequalled pattern recognition capability. Consequently, model evolution and application in the near future will centre around this focal point. Air defence system simulation must give the human element the credit it deserves in a complex and quickly changing environment.

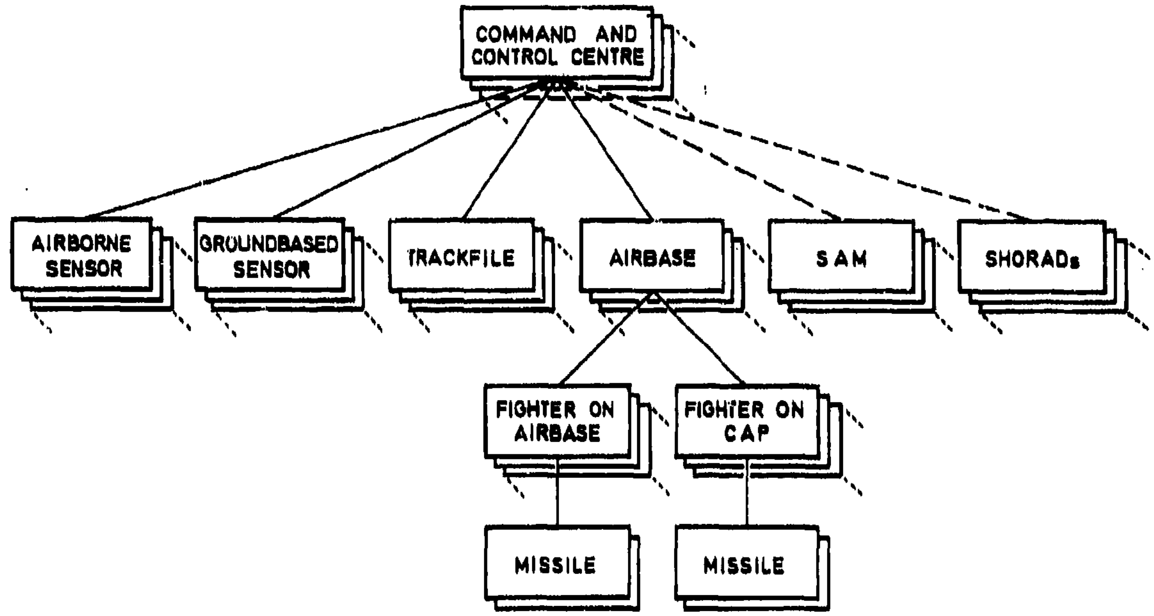


Figure 1: Conceptual model structure of the defending side

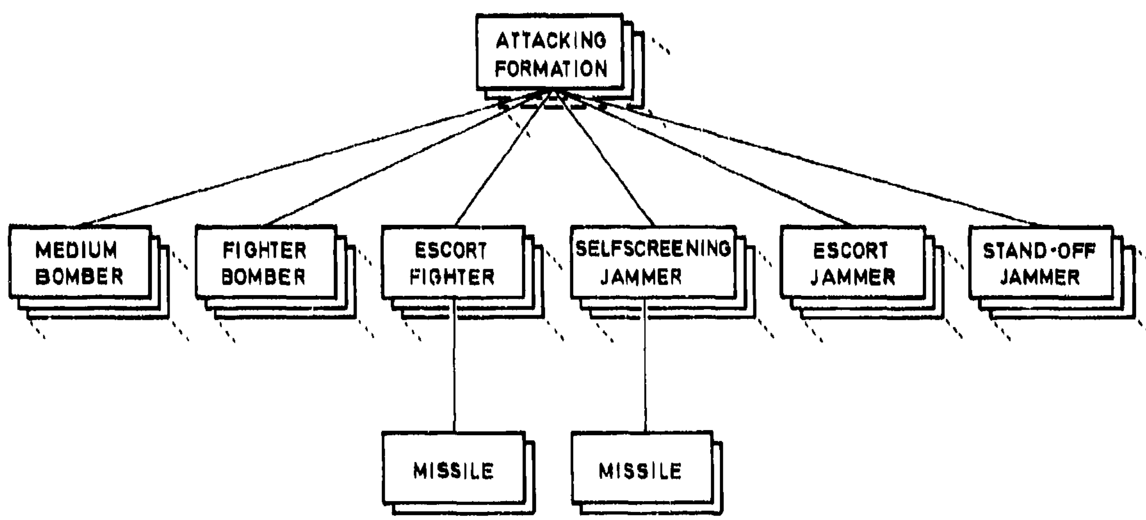


Figure 2: Conceptual model structure of the attacking side

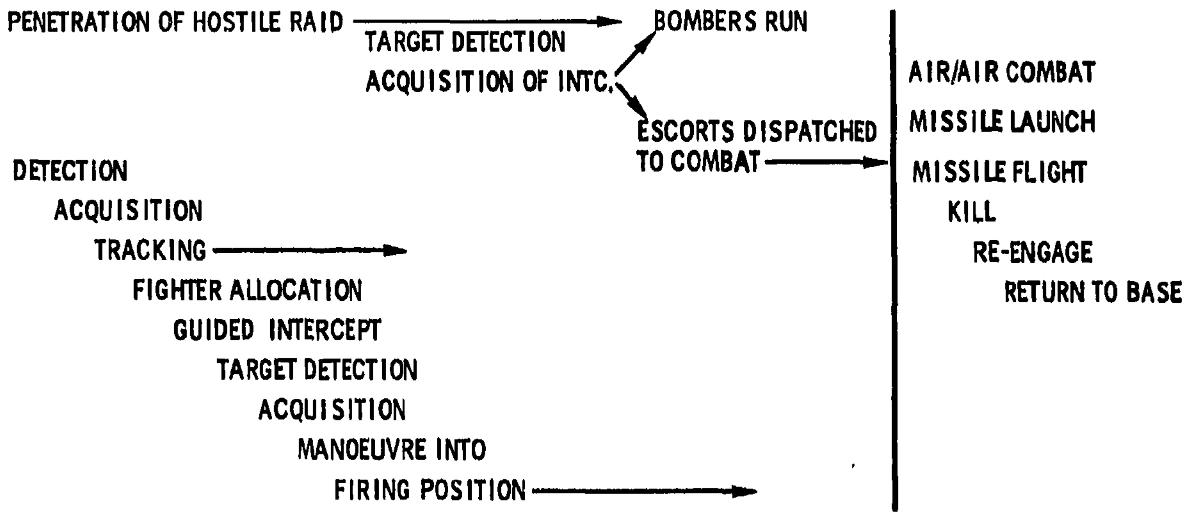


Figure 3: Sequence of modelled events

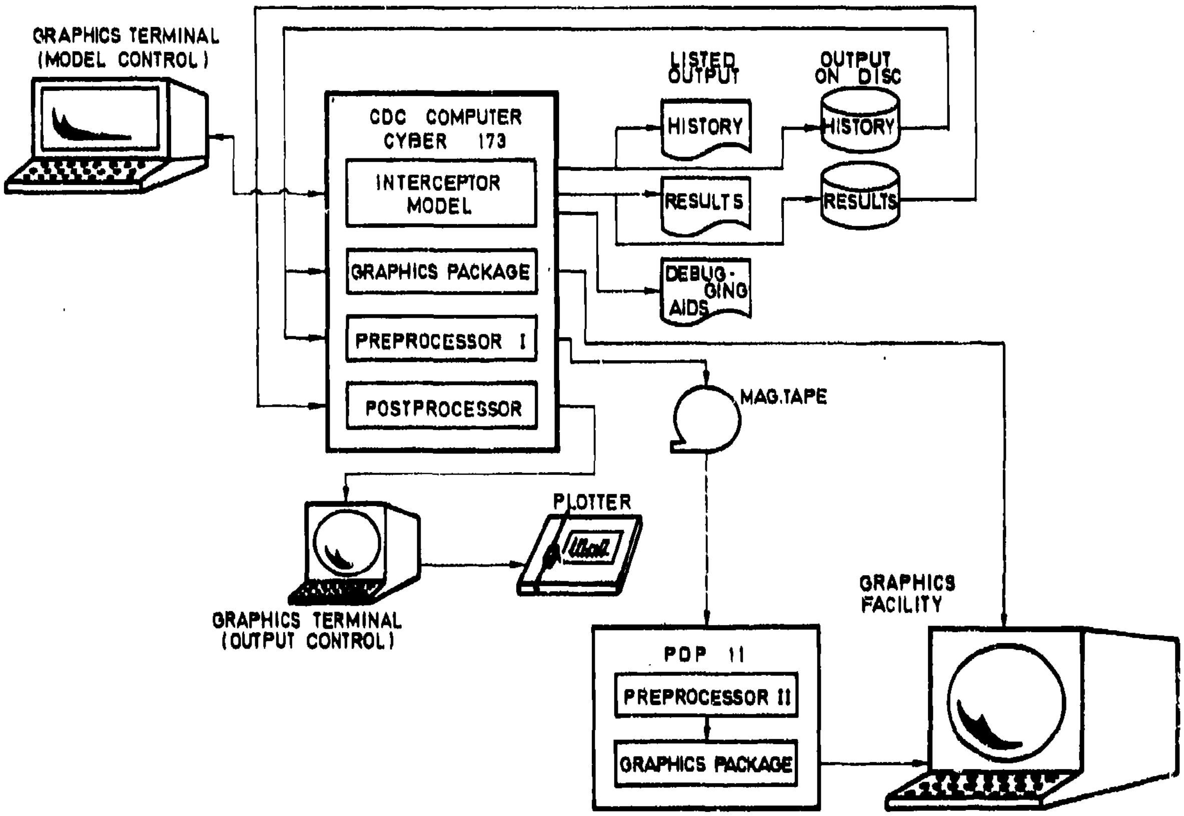


Figure 4: Hardware configuration

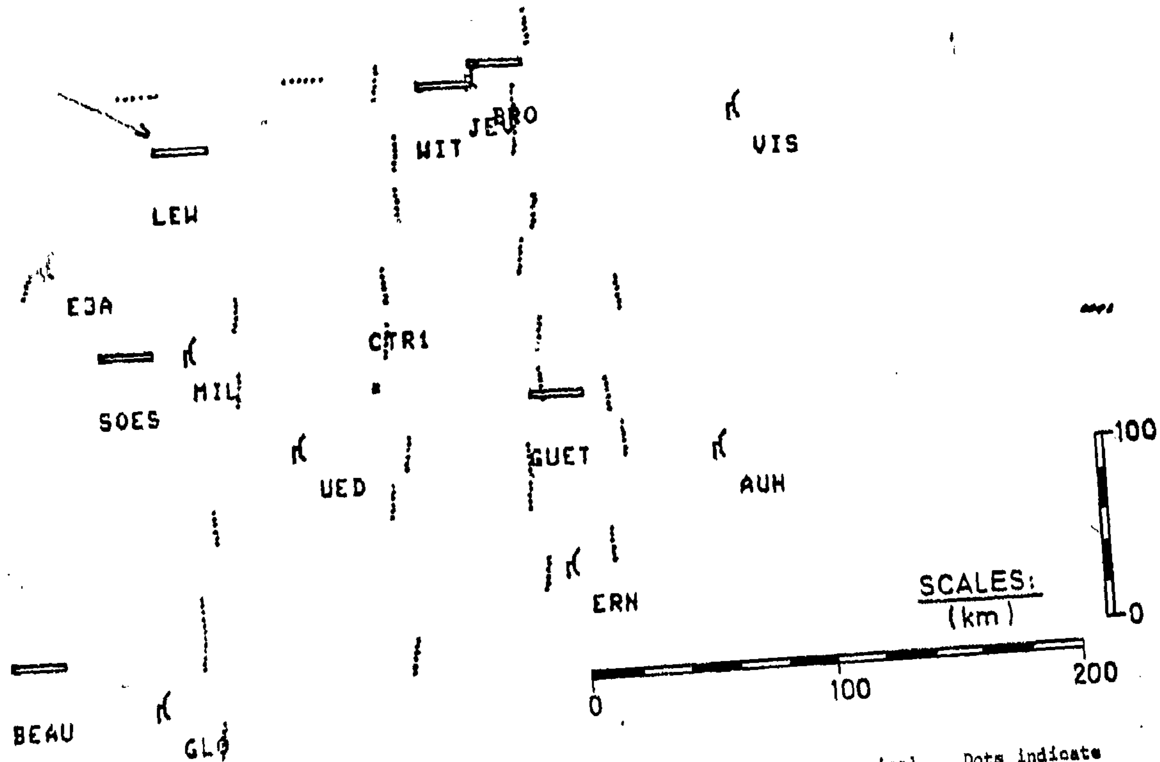


Figure 5: Example output. Hardcopy taken from the model control terminal. Dots indicate aircraft positions at 10 seconds intervals.

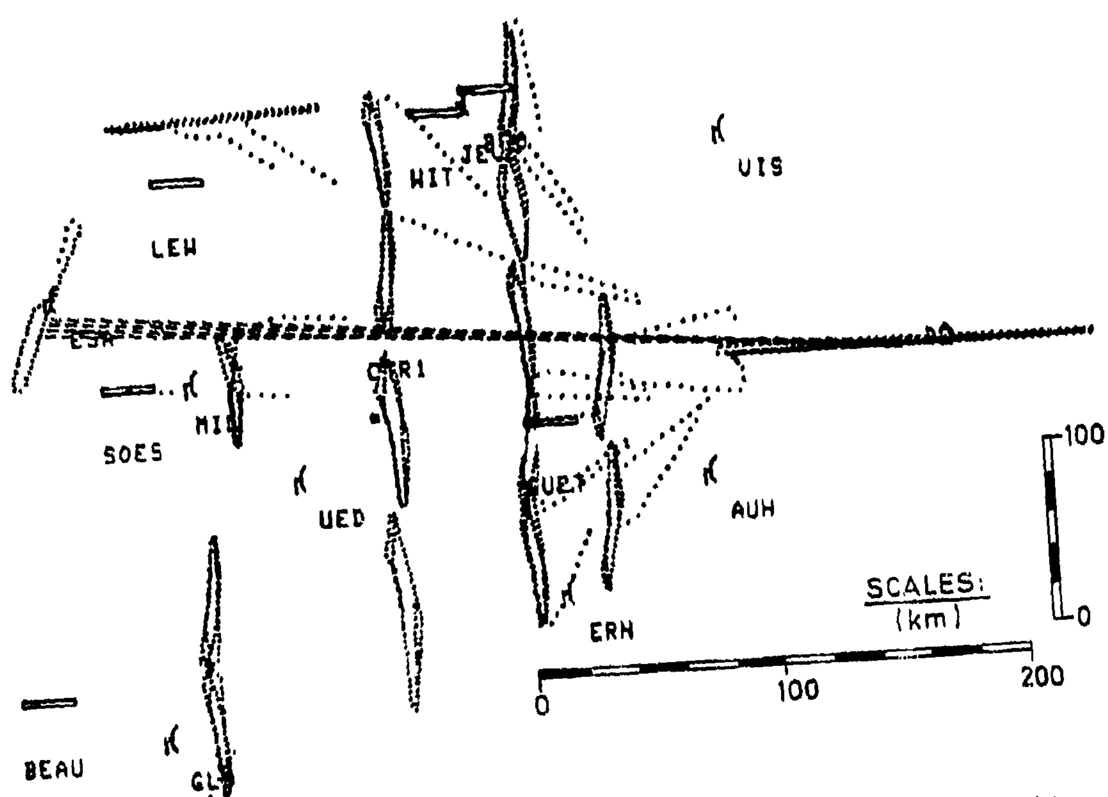


Figure 6: Tracks established are indicated by dashed lines from sensor to target. CAP fighters have been dispatched to the threat.

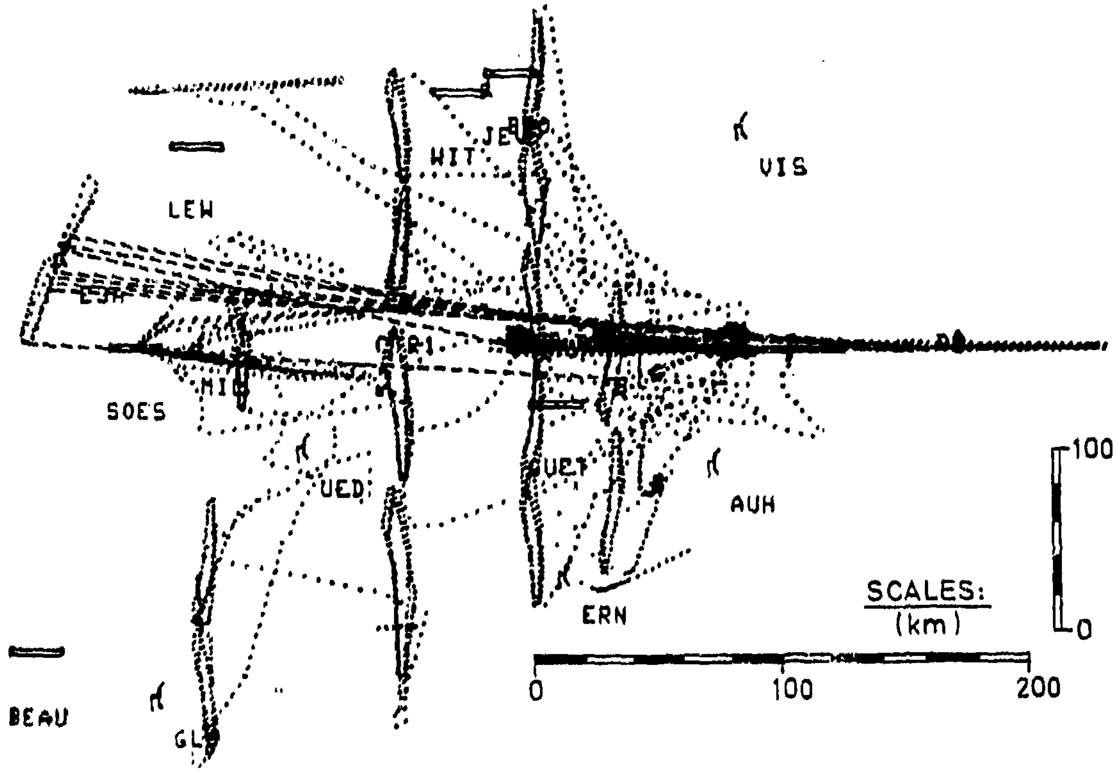


Figure 7: Full scale air defence operations and multiple air combat

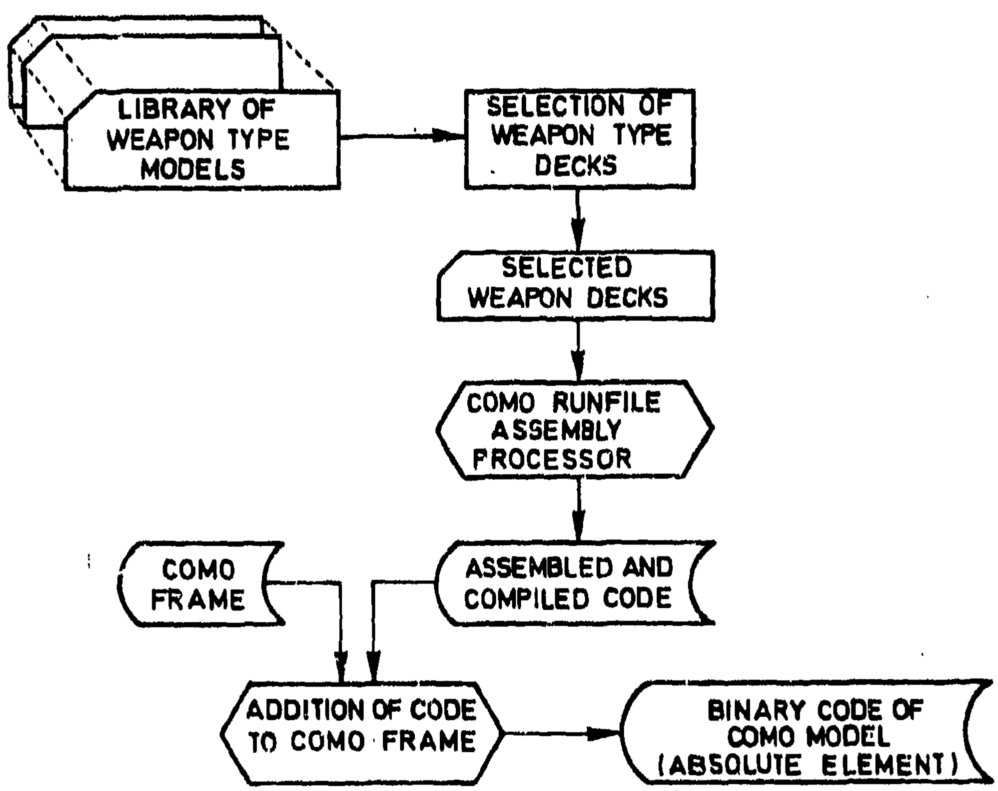


Figure 8: The process of generating a COMO model

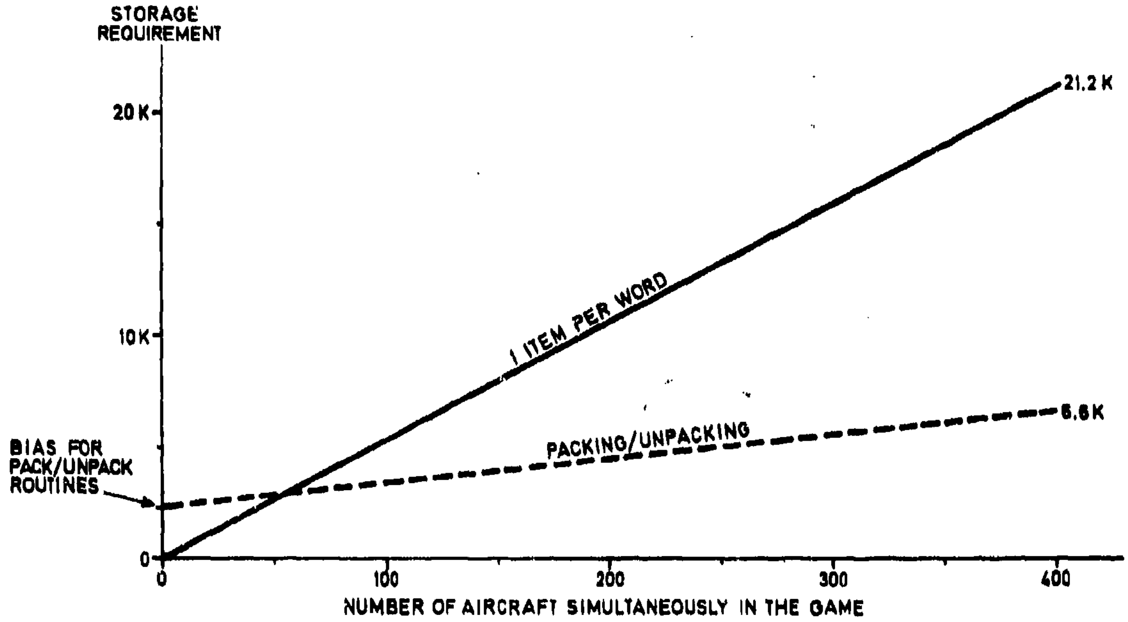


Figure 9: Storage requirement for variables as a function of aircraft simultaneously in the game

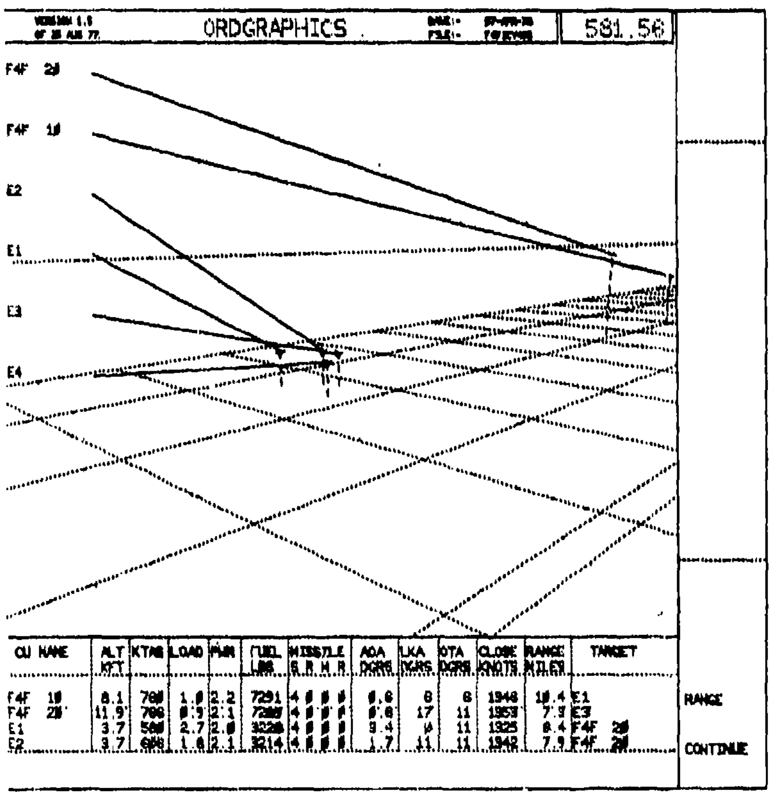


Figure 10: View into the combat arena of 2F4 aircraft fighting against 4 escort fighters (E1 ... E4). Grid size is two nautical miles. Game time is displayed in upper right corner of display area

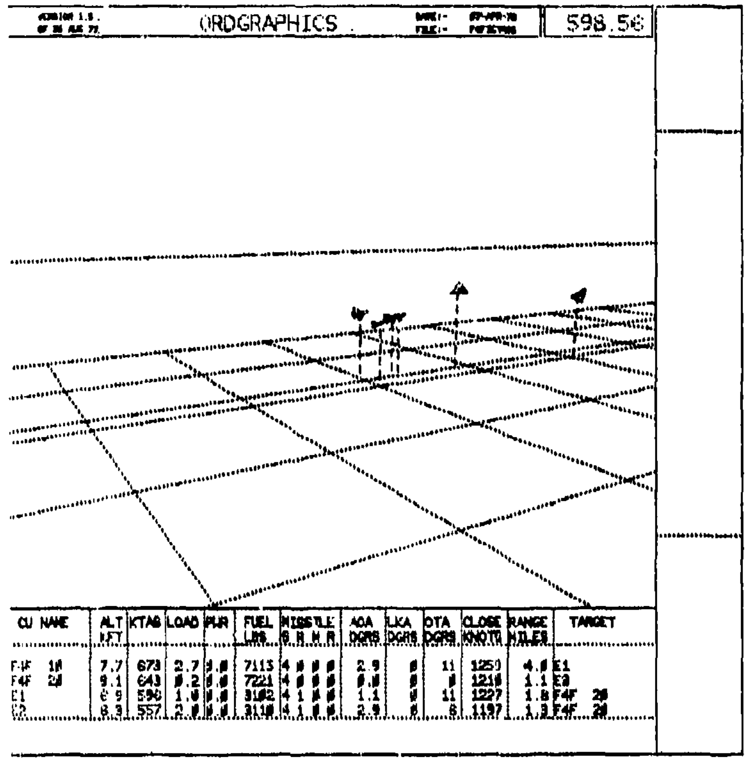


Figure 11: Head-on approach of the two opposing forces. First F4 (F4F 20) identifies visually

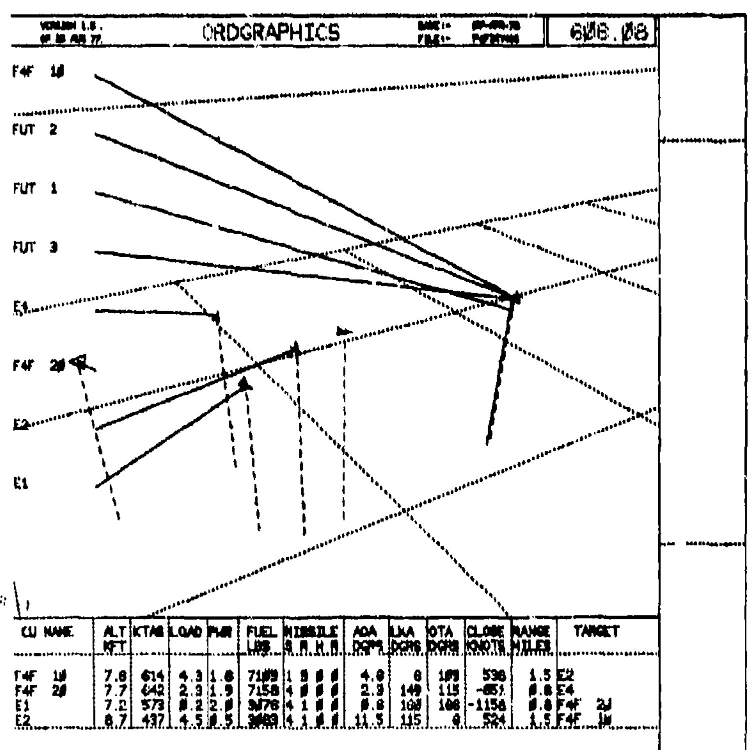


Figure 12: Second F4 (F4F 10) fires three all-aspect short-range missiles (FUT 1 ... 3) against identified targets

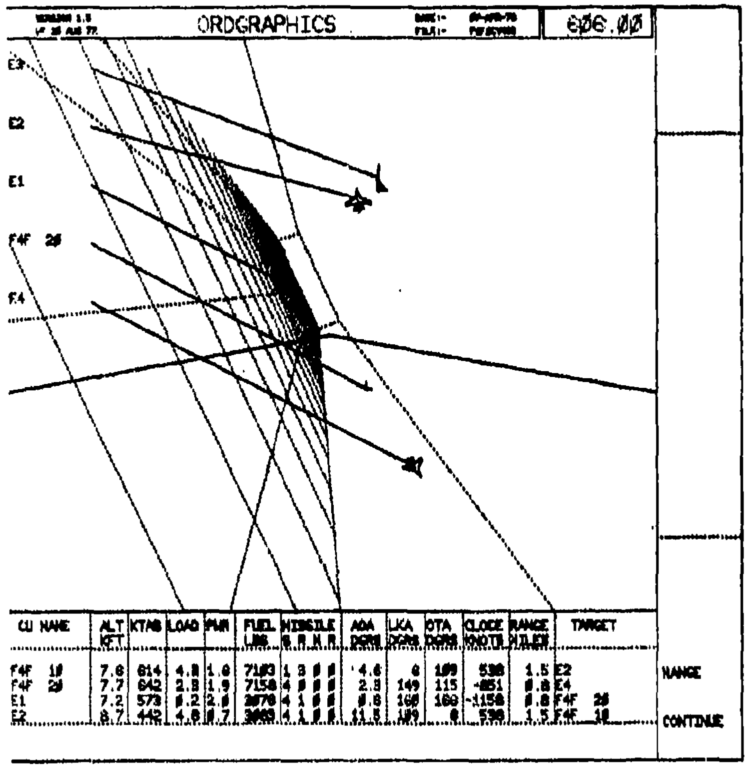


Figure 13: Pilots view from cockpit of aircraft F4F 1Ø at the moment of missile launch. Current target is E2. The roof-shaped line indicates the airframe of F4F 10 as seen by the pilot

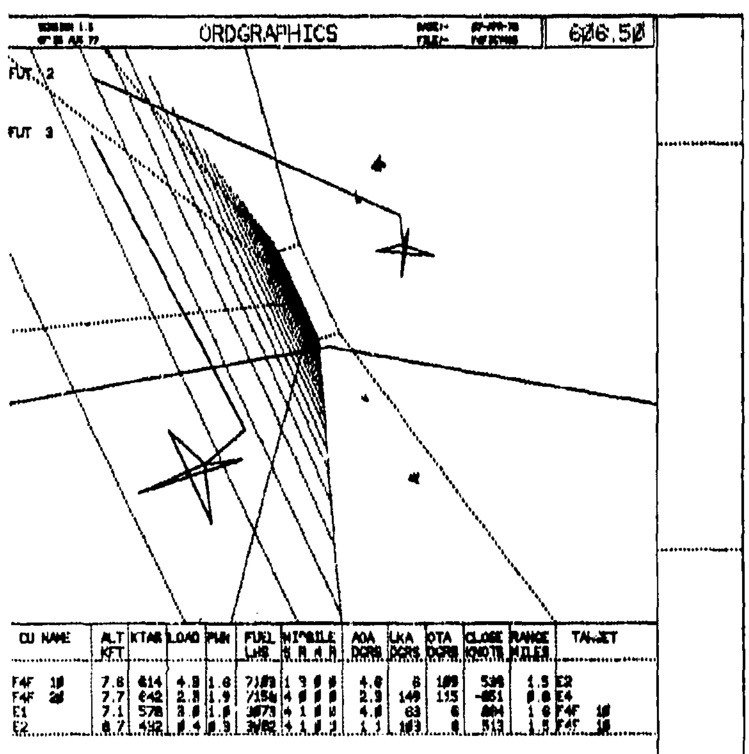


Figure 14: Pilot's view from cockpit of aircraft F4F 10, a short time after missile launch

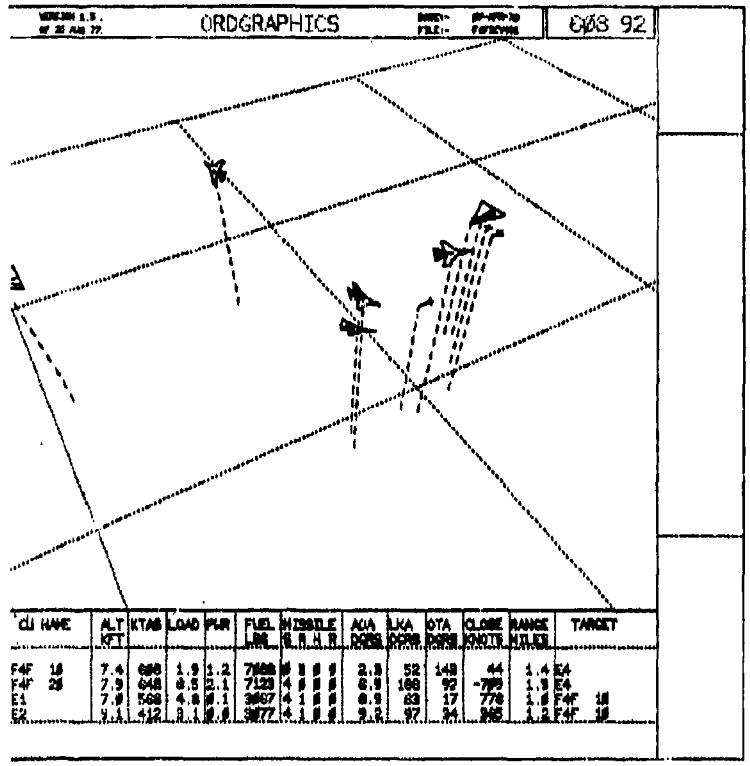


Figure 15: View into the combat arena, three missiles approaching three different targets

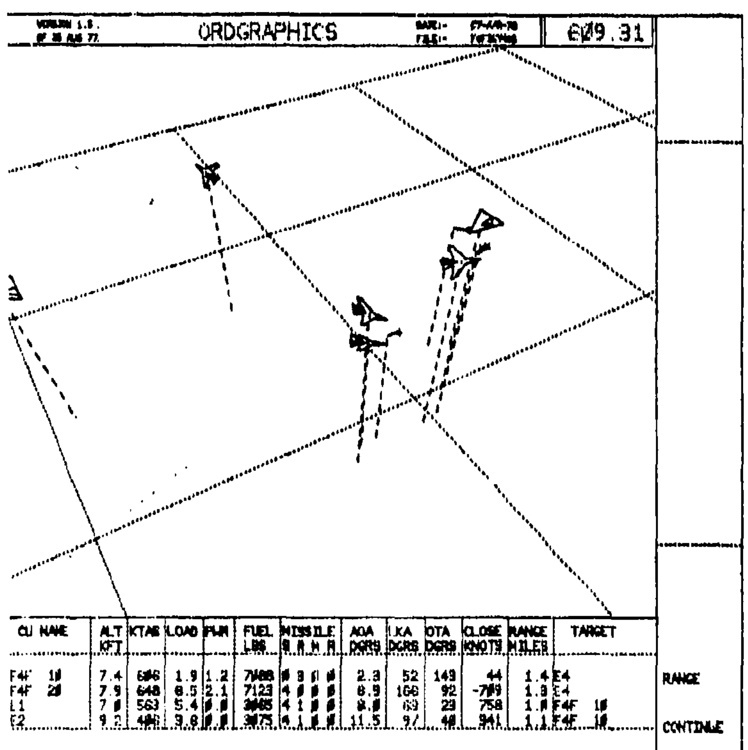


Figure 16: F4F 10 firing its last missile against target E4

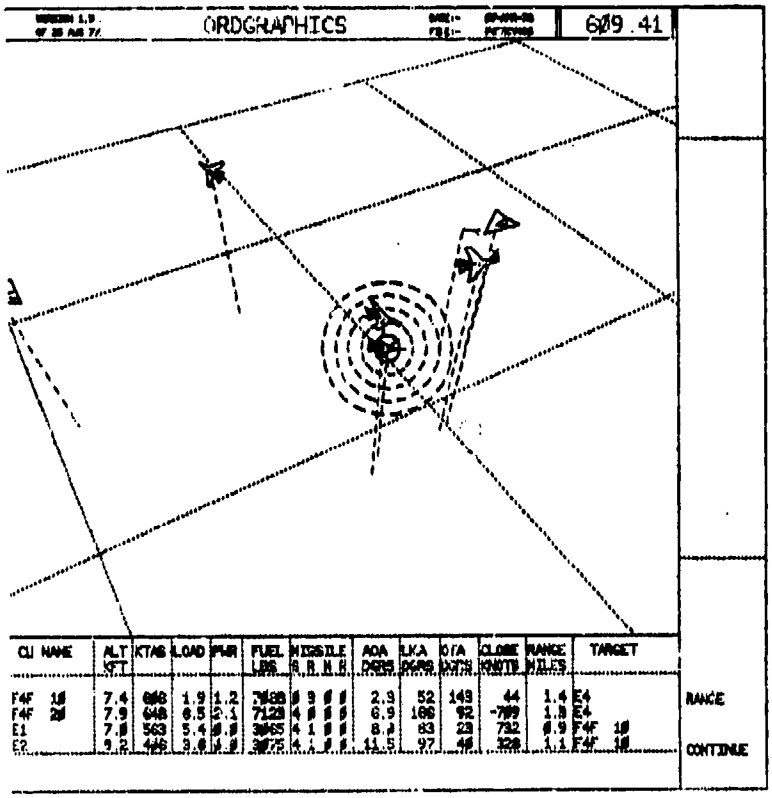


Figure 17: Kill of an aircraft

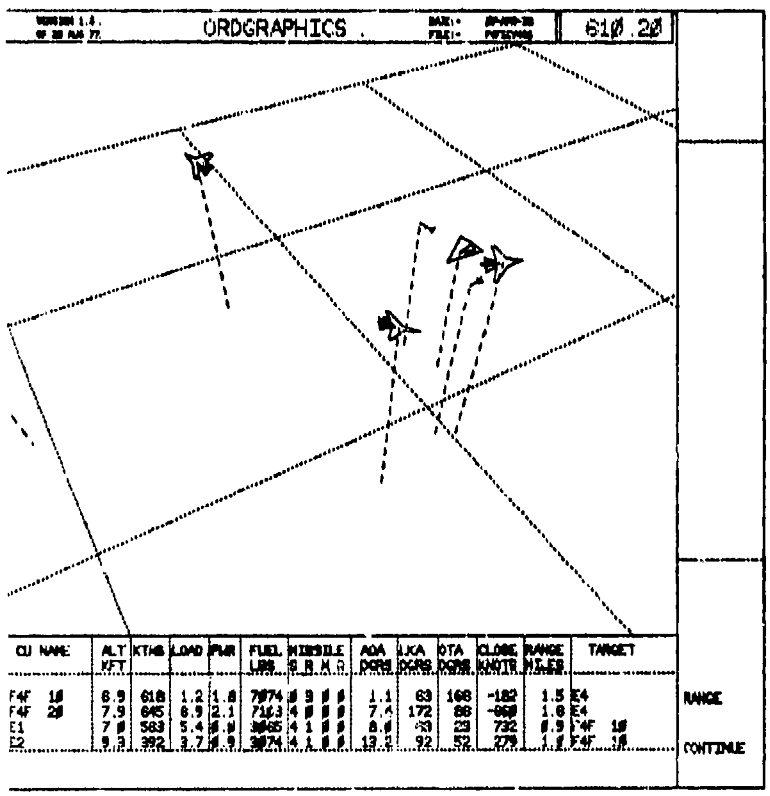


Figure 18: The 2 versus 4 air combat converted into 2 versus 3, however, with one aircraft having no missiles left, and two missiles still approaching their targets

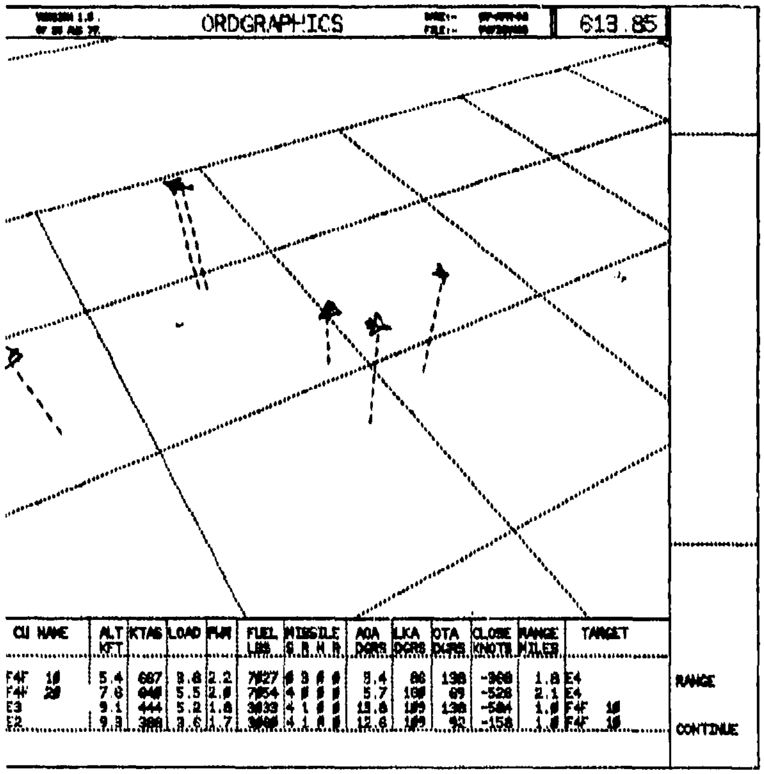


Figure 19: Missile 3 missed its target, missile 4 impacting on its target

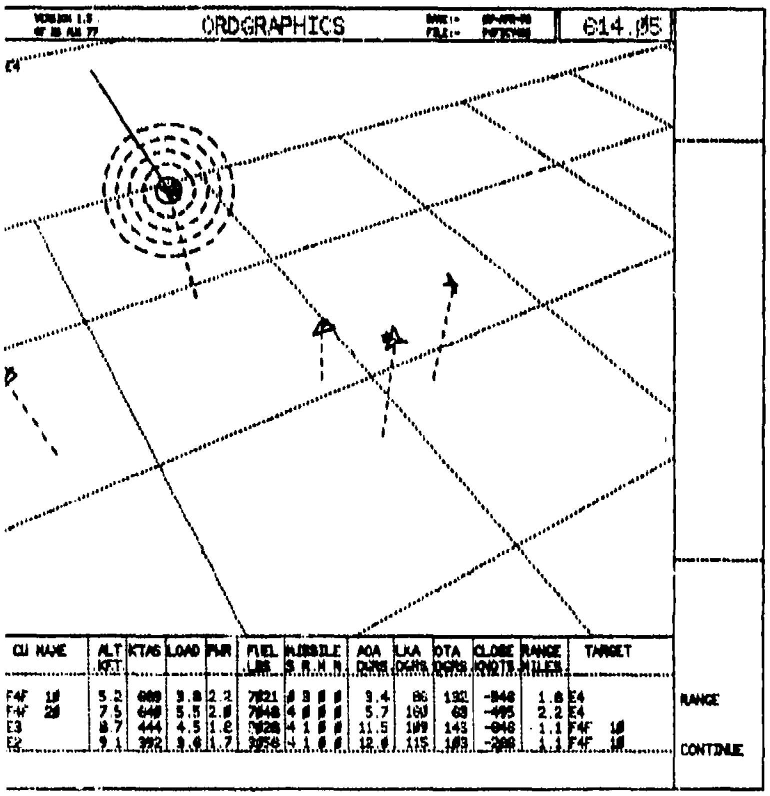


Figure 20: Explode of missile 4 resulting in a kill. The 2 versus 3 engagement converted into 2 versus 2

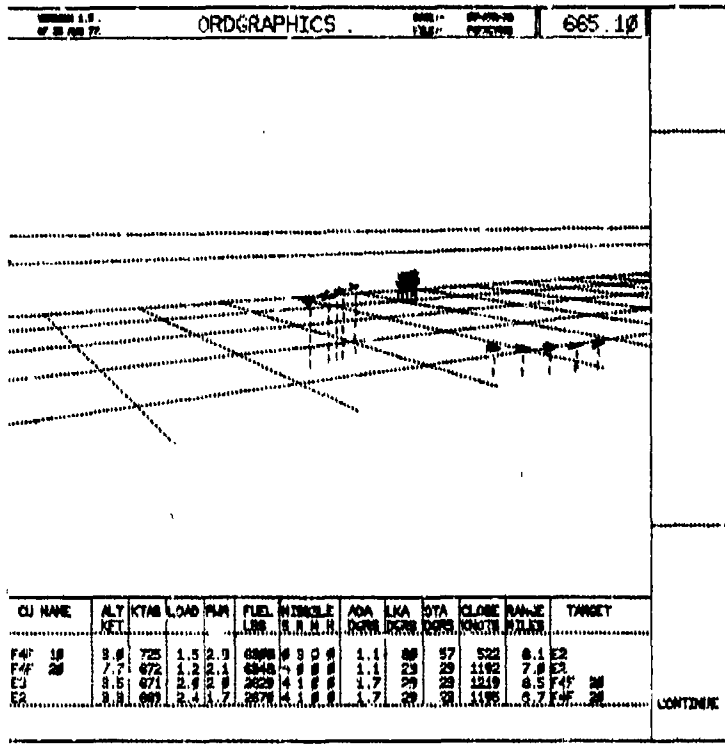


Figure 21: F4F 10 disengages, F4F 20 returns to combat. The 2 versus 2 combat converts into 1 versus 2

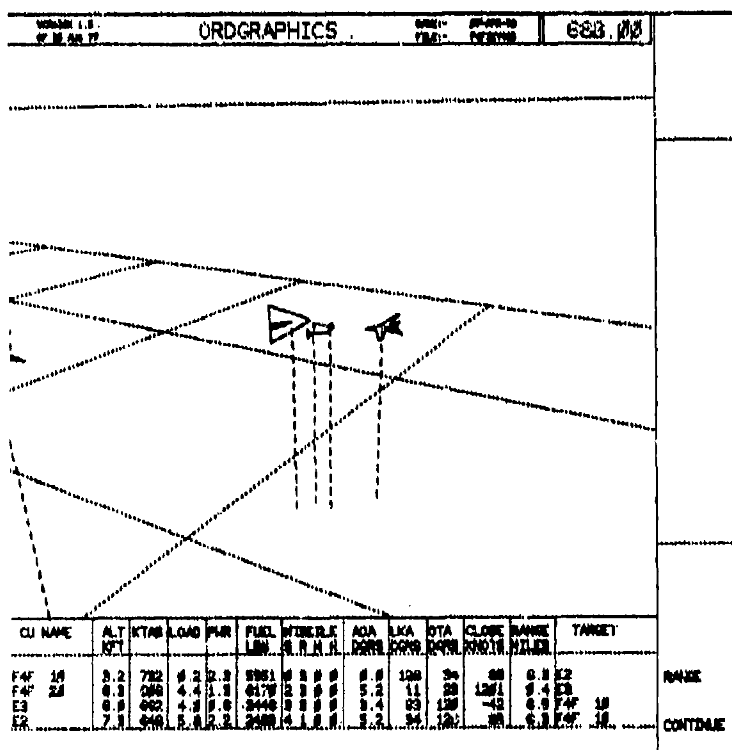


Figure 22: Head-on missile exchange

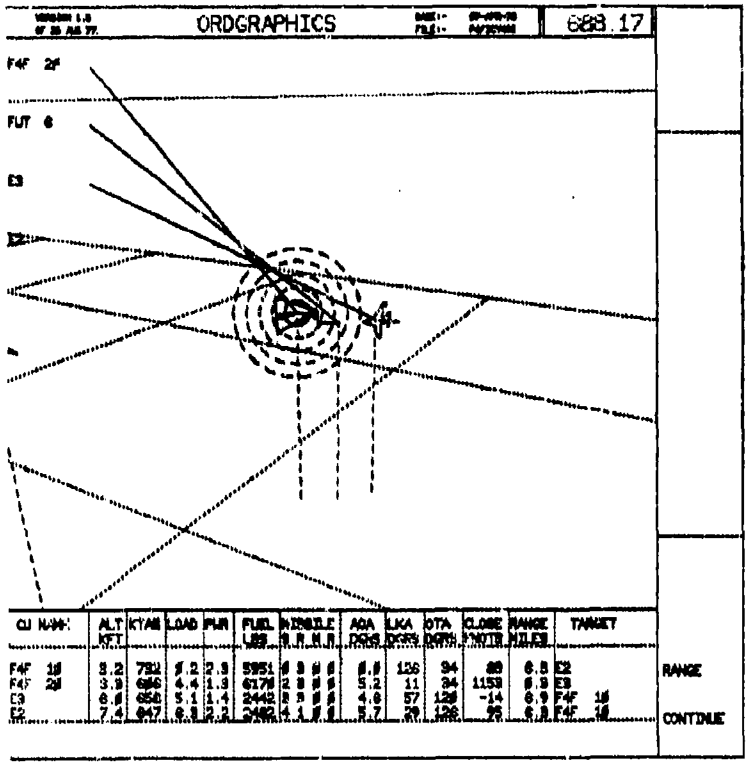


Figure 23: Kill of F4F 20, its opponent will survive

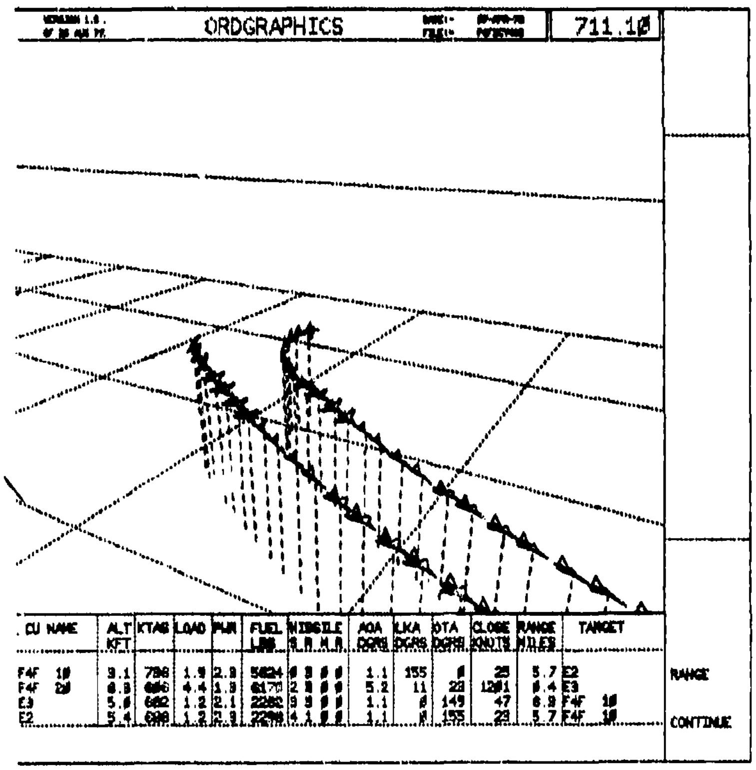


Figure 24: Surviving escort fighters leaving the combat arena

SIMULATION

WITHIN MILITARY AIR DEFENCE SYSTEMS

FOR TRAINING AND EVALUATION

Hans-Jochen Wunschmann
NATO Programming Centre
Blaarstraat 99
B-3700 Tongeren/Belgium

SUMMARY

Within automated air defence systems "simulation" is used to support "war gaming" and as a technique to study complex operational (real-time) software functions.

In this context simulation has the rather specific meaning of the generation of a synthetic radar picture which is input into the air defence system's hardware and processed by its software.

Such simulation systems enable war gaming for operational training and evaluation purposes for which the use of live aircraft is excluded for intelligence, cost, safety or geographical reasons.

To generate the simulated radar picture, which forms a variable model of the current air threat, computer programs separate from the system's real time software are involved.

These programs utilise flight-path models using known aircraft performance characteristics, as well as modelling of weather, terrain and radar receiver characteristics.

The different phases of war gaming within air defence systems are described, and finally the question of analysis and performance evaluation programs to permit the assessment of the performance of the system or its components achieved on a simulated scenario compared to that expected is addressed.

INTRODUCTION

1. Within automated air defence systems "simulation" is utilised to support "war gaming" at different tactical levels of the air defence organisation. In line with the theory of games the combat between air attack and air defence can be viewed as a two-person-zero-sum game. In principle there is one attacker who seeks the greatest possible gains (the destruction of targets) and a defender who attempts to make these gains as small as possible. The attacker has a large choice of possibilities he must choose :
- the targets for the attack ;
- the type and number of aeroplanes ;
- the flight profile (manoeuvres), route and flight tactic ;
- the weapon yields ; and
- the time of attack.

The defender has a more limited choice of possibilities, he can select :
- the location of weapons and their tactics ;
- the distribution of his defence resources among the targets subject to attack ;
- the employement of his resources over time.

2. The purpose of gaming in air defence is to serve :
- as a training and indoctrination technique ;
- as an analytic tool by which different concepts or plans can be investigated ; and
- as an evaluation tool for operator and system performance.

The "rules" for the games are normally the current operational procedures supplemented by scenario dependent additional information, (i.e. the enemy's and own forces location, capabilities, intention as well as the development of the political and military situation which leads to the conflict to be "played"). In principle the games are run in a "closed-play technique", where uncertainty and intelligence are included, and the play is controlled and monitored by a "Directing Staff".

3. Due to certain peculiarities, the "games" played in our present air defence system appear somewhat different than the standard application of the theory of games. The most important ones to be noted are :
- The expected course of action of the attacker is simulated by a predetermined computer generated string of events forming a model of the air threat supplemented with chronological oriented scripts of tactical action events ;
- The defender utilises the normal operational hardware and software functions of the air defence system to react to the threat in accordance with current operational plans and directives. (Fig. 1).

It should be noted as well that air defence personnel use the term "exercise" instead of "war game", a "game" using simulated inputs is called synthetic air defence exercise (SYNADEX).

4. The type of analysis to be performed after the "game" is determined by its objective or purpose and the tactical level of the "players". In general an outcome-oriented analysis will be performed which can be regarded as a summary of "what happened" in the course of the war game. The events compiled will serve as a data base for operator and system oriented performance evaluation and to draw conclusions which feed back into the operational environment and into the objectives of follow-on gaming.

SIMULATION SUPPORT FOR WAR GAMING

5. Within automated air defence systems "simulation" has the rather specific meaning of the generation of a synthetic air situation upon which "players" from the planning and tasking level down to the execution level of the organisation may take the same decisions and actions as for a real air situation, and which will respond to these actions similarly to the real situation. In contrary to the standard application of simulation the system to be manipulated is retained and not replaced by a software model. The inputs to this sytem, however, are simulated and represent a dynamic model of the air threat in the form of a synthetic radar picture. One may look at this configuration as a "People and Computer Model", because both people and computer software and hardware are embedded in an overall model comprising the own air defence system and its air assets as well as the opposing air threat. (Fig. 2).

6. The primary purpose of simulation in the air defence system is to play those operational scenarios which cannot be exercised during peacetime live activities and to exercise the system at low cost. Fig. 3 shows a broad example scenario.

In peacetime exercising of real air defence operations are limited in number, duration, magnitude, and contain many artificialities. Particular limitations are due to :
- national regulations and restrictions (i.e. limited supersonic flying, prohibited geographical areas, air traffic control aspects) ;
- air safety constraints ;
- peacetime restrictions in using electronic counter measures (ECM) ;
- impact of variables which cannot be controlled (i.e. weather, equipment status) ;
- limited availability of aeroplanes (to represent the attacker) ;
- costs involved, and
- security aspects.

These constraints mean, that war games utilising the "real world" have a limited value with regard to operational analysis and system training i.e. :
- a model of the air threat (attacker) and the own situation and capabilities (defender) composed of real elements does not cover the expected situation to the required extent ;
- "replays" of live games are expensive and will not reproduce the planned scenario to the extent required due to various variables which cannot be controlled.

7. Maximum transfer of learning from a simulated situation to the real work can only be achieved if adequate simulation takes place. It is therefore imperative that the simulated inputs generated for an air defence war game (commonly called synthetic air defence exercise) must replicate the real life threat environment to a sufficient degree and thereby assist in revealing critical air defence situations, system deficiencies and inadequacies. This is realised by providing the following features with the simulation package implemented in the air defence ground environment :
- the total number of simulated flight paths allows the generation of saturation conditions for the system and the operator ;
- all flight paths are filtered before display and processing through comprehensive models of the real radar coverage diagrams of all radarsites involved in the war game ;
- intensity calculations are performed to approximate realistic "painting" of simulated plots and jamming as a function of radar cross-section, range and radar receiver characteristics ;
- electronic jamming and chaff are realistically correlated with the appropriate simulated jammer tracks and subject to intensity calculations ;
- all simulated flight paths can be programmed to reflect the currently known or expected flight profiles, envelopes, performance characteristics, approach and attack tactics and "targeting" of NATO and non-NATO aircraft ;
- simulated NATO interceptor type aircraft utilising models of their performance characteristics can be manoeuvred against the threat ;
- all simulated data inputs are processed and reacted upon as for real live data.

It should be noted, however, that the simulation system procured is mainly designed to train, test and measure the internal flow of tactical events and operational functions of the NATO air defence ground environment. The efficiency of the weapons systems employed for defensive actions is not included in the simulation process. In addition to realism the air track parameter considerations are very important for analysis purposes since they deal with detection and tracking capabilities within the air surveillance function of the system and direct attention upon available reaction times. To avoid design simplifications that degrade realism and thwart valid analysis and evaluation of war gaming the huge amount of data involved is processed by an appropriate computer program developed for the NATO Air Defence Ground Environment (NADGE) system which in addition reduces the amoung of manual labour involved in producing the simulated inputs and analysis results.

8. It must be stressed that simulation is an important vehicle for analysing and evaluating site or system performance. This requires standard mission design with controlled environmental conditions and supplemented with a variety of "stress inputs" in accordance with the current training objectives. Performance observed during war games of equivalent difficulty can then be compared as a measure of improvement or degradation. Depending on aim, scope and volume of the planned war game and the command levels involved the information needs of the various users for analysis purposes are different. The exercise designers, therefore, must consider the analysis objectives and consequently the methodology of the analysis and evaluation programs. The scope and configuration of the simulated air situation and the simulated operational environment must be tailored to the training and analysis requirements. The aim of expanding the scope is to increase the number of actual information and control inputs to be processed. The larger war games in scope and configuration, the less the requirement for simulator personnel, i.e. those who are required to simulate the actions and responses of the system elements that are not directly involved in the exercise. In a large scale war game, the only simulated inputs are the sensor data and events (stress inputs) as injected from an incident list prepared by the exercise planners.

THE NADGE SYSTEM AND ITS ASSOCIATED SIMULATION HARDWARE AND SOFTWARE

9. The NATO Air Defence Ground Environment system together with the national systems of France and the United Kingdom form the air defence system for the whole of NATO Europe (Fig. 4). This complex system consists primarily of :
- radars,
- computers,
- electronic data transmission facilities, and
- communications.

About eighty sites are netted with the data links for air track data exchange and following a continuous North-South sweep from Norway through Germany to Turkey. This system is directed by the different NATO Air Defence Command levels and provides continuously :
- a recognised (identified) overall air picture, and
- capacities for the control and monitoring of air defence weapons.

The sequence of functional and operational events performed are shown in Fig. 5. Included in the hardware and software functions of the NADGE sites are simulation facilities. These support realistic war gaming in the form of exercises using simulated inputs. The war games may range in scope from site centred exercises to a system-wide scenario involving the appropriate tactical command and control elements. With regard to system-wide war gaming it must be pointed out, that hardware and operational software are specific to the particular air defence system for which they are procured. The programs available in the NADGE system to generate the simulated air picutre are to a great extent, independent of the particular automated system since it is often a requirement that the simulated air situation be displayed simultaneously with units with differnet systems.

10. The NADGE simulation System comprises three major elements :
- off-line software to generate simulated air track data, jamming and chaff on magnetic tape, which is input to the hardware for war gaming ;
- hardware to produce simulated radar responses on the operator's data display consoles, route the simulated data into the main processor and control the simulation functions ;
- on-line (real-time) simulation software, which time-shares the central processor with the operational (real-time) software and in conjunction with the hardware processes the simulated data inputs.

11. The NADGE Simulation System will primarily produce a simulated threat and operational environment for the system operators. In the design of the on-line (real-time) simulation software every effort was made to permit the system to operate in a simulated environment in the same way as it does in the real air defence environment. For this purpose the real operational data base of the system is used in simulated operations. In addition the processing of simulated radar plots by the correlation and tracking software is - as mentioned before - the same as for real plots. This feature - outside war gaming - would allow, for example, the evaluation and optimisation of different tracking logics using defined simulated radar inputs.

12. The overall NADGE simulation software package utilises :
- a dynamic model of the current intelligence air threat scenario which includes existing aircraft kinds and numbers, their tactics, profiles, sortie rates, targeting, and performance characteristics as well as the application of electronic warfare (ECM) techniques (electronic jamming and chaff), and some weather data (winds aloft) ;
- dynamic models of the performance and tactics of several NATO air defence interceptor aircraft ;
- static models of the performance of some NATO surface-to-air missile (SAM) systems ;
- comprehensive static models of the technical characteristics and detection capabilities of all NADGE air defence ground radars including some form of simulating the effect of jamming.

13. The general concept in generating a simulated air picture (Fig. 6) is to have a library on magnetic tape ofall kinds of friendly and hostile flight path models which are derived from the latest intelligence information. This "target library" may be updated continuously and contains several thousand individual flight paths covering the whole area of NATO Europe. Depending upon the purpose and objectives of the war game, the user selects out of this library the flight path models required. With this information and the desired activation times of the selected flights, a "master flight path tape" is generated containing the overall air situation of a war game as it develops over time. During this process the appropriate software calculates for all radarsites participating in the war game where and when each individual simulated flight path is within theoretical radar coverage of a site. Track loads exceeding the computer track store capacity of the participating sites are thus avoided. From the "master tape" the individual air situation of each site is split off using a model of the real radar coverage. These magnetic tapes (called "raid tapes") then form the simulated radar input for war gaming.

PHASES OF AIR DEFENCE WAR GAMES

14. The war games or exercises "played" within the air defence ground environment include, as mentioned before, the human player and depend, therefore, on human judgement and decisions. In addition it must be emphasised that these games serve more the purpose of training and operational analysis than of scientific research. This means that the large number of political, economic, and logistic factors which influence military operations play more the role of background information than of active inputs into the game. In principle there are four phases involved in the game activity which are design, production, play and analysis (Fig. 7 and Fig. 8).

15. The design phase starts with the definition of the purpose or objective of the game which dictates :
- the selection of the geographical location, duration of the game, and the weather ;
- the composition, location and state of readiness of the defender's and attacker's forces ;
- the development of the air threat and targets to be attached ;
- sequence and timing of tactical event inputs (i.e. development of the alert status, tactical action results) ;
- the definition of a fictional political, economic and logistical scenario that led to the confrontation and its further development over time.

Having developed these simulated inputs the rules of the game, tailored to the particular game situation, will be elaborated. These rules include any restrictions, attrition factors and all kinds of "planning factors". In general terms the design reflects all events and factors required to satisfy subsequent analysis and evaluation purposes ; it must, however, as well ensure a challenging play phase. In the Air Defence Ground Environment most war games are designed to test the efficiency of the system and its operators against the predefined threat scenario which represents a model of the real threat expected. The simulated threat inputs, therefore, should be tailored by the designing team to trigger answers to those analytic questions upon which operational analysts or evaluation teams will base their findings after the game. These questions are normally, for example, along the following lines :
- How early did the system pick-up targets ?
- How many and what kind of targets remained undetected or were lost ?
- Was track identification (i.e. FRIEND or FOE) correct and in time ?
- Dit the system allocate targets to defensive weapons and achieve "kills" before the defended areas have been entered ?

The answers to this kind of questions then lead to findings about the efficiency or deficiency of :
- System operations personnel from the Command level down to the console operators.
- Operational procedures, and
- The system's hardware and software functions involved.

16. In the production phase the design specifications are transferred into formats acceptable by a special simulation preparation software. These computer programs have been developed by the NATO Programming Centre (NPC) and are in field use to generate the simulated air situation on magnetic tape and utilising the threat and radar models explained before.

17. Typical, for the play phase of a two-sided air defence game (or exercise) is, that the attacker's course of action is preset by simulated inputs from magnetic tape, but that the friendly team is allowed to play free in accordanxe with the development of the simulated threat and the defender's estimate of the situation. The game is started by an intelligence briefing for all participants which describes the general and special situation and events that initiate the conflict. All moves made in the game are monitored by a Directing Staff which clarifies any confusions, enforces the rules, evaluates and assesses the result of each move, initiates subsequent event inputs and injects tactical action events as dictated by the design. All actions taken by the players (defender) as well as the development of the air situation are recorded on magnetic tape.

18. The analysis phase of war games performed within the NADGE system is supported by a computer program package developed as well by the NPC. This software has been designed to handle the great volumes of recorded operational data and to enable evaluation teams and system analysts to :
- analyse and evaluate operator actions and system functions ;
- test the performance of the NADGE operational (real time) software ;
- compile a data base which allows derivation of evaluation criteria.

The output of these analysis programs is straight facts in a convenient and easy to read format, while evaluation programs in addition compare these results to defined standards and, if desired, to past performances.

THE ANALYSIS AND EVALUATION PROCESS

19. The operational data recorded within the NADGE system on magnetic tape may be processed after the game by the NADGE analysis software which provide for flexibly selecting and organising this data in the forms most efficient for the user. One fact to be observed is that the information needs of the various users are markedly different and call for providing varying levels of detail. The major functions of the overall analysis and evaluation process are :
- to present objectively all significant air track related events, operator actions and system functions ;
- to produce figures of how much has been achieved compared with the expected as presented by defined simulated data input or appropriate evaluation criteria.

20. During the design phase of the evaluation software those data elements contributing to system and operator performance had to be identified from the huge recorded data base. Although skilled system analysts and programmers with knowledge of the real-time operational NADGE programs and its associated recording system can perform functional analysis of system activities and information flow, they can at best formulate candidate analysis and evaluation measures and output formats. It was left, therefore, to those personnel with direct experience in system operations to provide ultimate judgements as to design requirements, identifying data needed, and finding evaluation standards. The problem of determining whether the mission performance of an individual unit or a system was "good" or "bad" is compounded by :
- the complexity of the interrelationship in factors of the air defence system's environment ;
- the complexity of the NADGE system design ;
- the definition of evaluation criteria and standards.

It is felt, therefore, that perfection in evaluating air defence systems and units by comparing recorded events to absolute and stringent standards which satisfy all aspects can hardly be achieved. The approach taken to find a fair solution was to present "facts" and leave it up to the user to define standards for comparison with the results (facts) achieved, and to "weight" the inter-play of complex factors and variables in an operational environment.

21. Furthermore, it should be noted, that the interrelationship between the variables of the operational environment and mission performance can neither be fully predicted nor strictly controlled by a play scenario and a directing staff. In other words; even with a standard game design there will be no war game exactly like another. The impact of these factors cannot be measured by the machine and the user must take care of proper weighting. The figures produced automatically can, therefore, form only part of the overall analysis and evaluation process. It remains up to the command/analysis personnel involved to interpret the results and draw the correct conclusions from them and initiate feed back into the operational environment as well as the purpose and objectives of subsequent war games (Fig. 8).

22. As mentioned before the operational data recorded during the "play phase" contains a compilation of straight facts gathered during several hours of "play time" for hundreds of different air tracks. The analysis programs developed in principle compare and correlate the recorded events on a track by track basis with the prescripted simulated data which was real time input into the system during the "play phase" of the war game. The expected situation and what the system produced after processing this input is thus represented (Fig. 9). The result of this comparison produces objective figures of what has been achieved during the "play phase", and which may be arranged in the form of easy to evaluate diagrams. The answers to the analytic questions defined in the "design phase" may thus be answered. Some example diagrams using fictitious data are shown in Figures 10 to 13.

CONCLUSIONS

23. War gaming within controlled environmental conditions and based on carefully designed simulated inputs is considered a powerful and challenging vehicle by which to train and analyse an automated air defence system or parts of it. The system described, which is in field use throughout the NADGE system, can highlight problem areas in site operations and system functions. Depending on the type of problem encountered, one can investigate possible causes or design further special war games to discover whether the problems encountered are repeated or to collect more data. In any case the strength and weaknesses of site operations or system functions must be taken into account in the design of future war games or analysis schemes. The small expenditure of manpower that is required to obtain results from the analysis outputs in a form of immediate use to evaluation personnel and system analysts seems to be a small price to pay and is irrelevant when compared to the cost and planning time required for live flying activities.

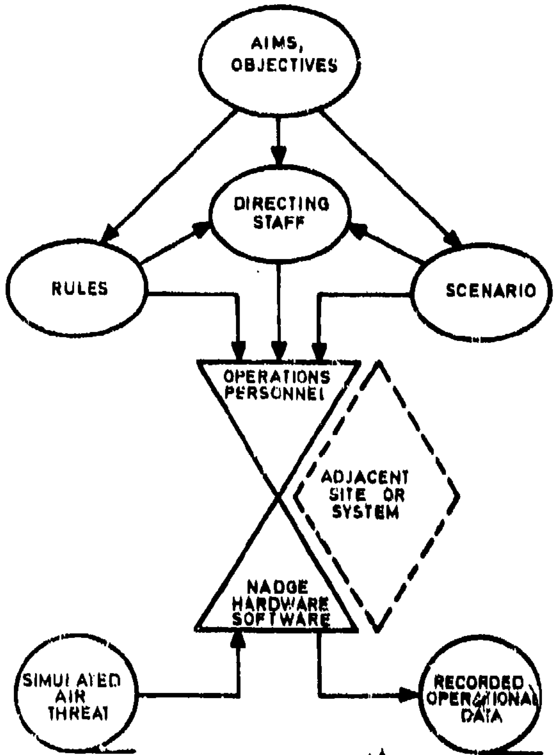


Fig.1 Elements involved in war-gaming

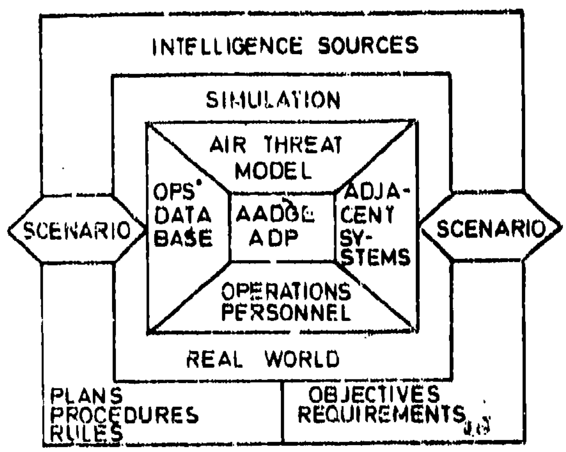


Fig.2 War-game overall environment

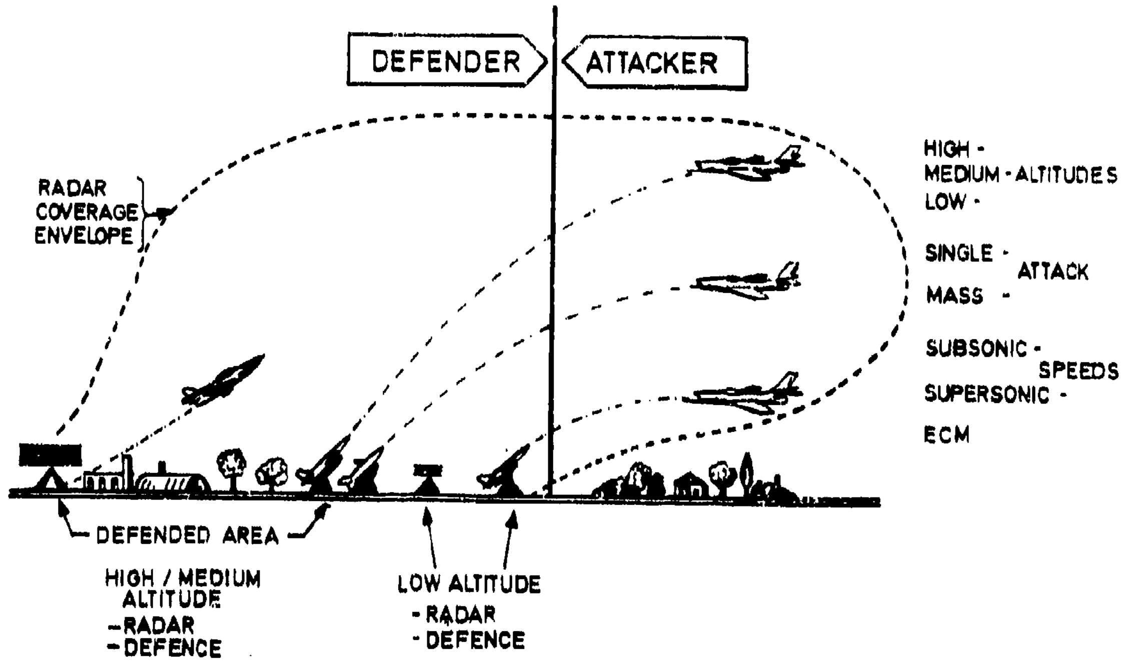


Fig.3 War-game scenario basic concept

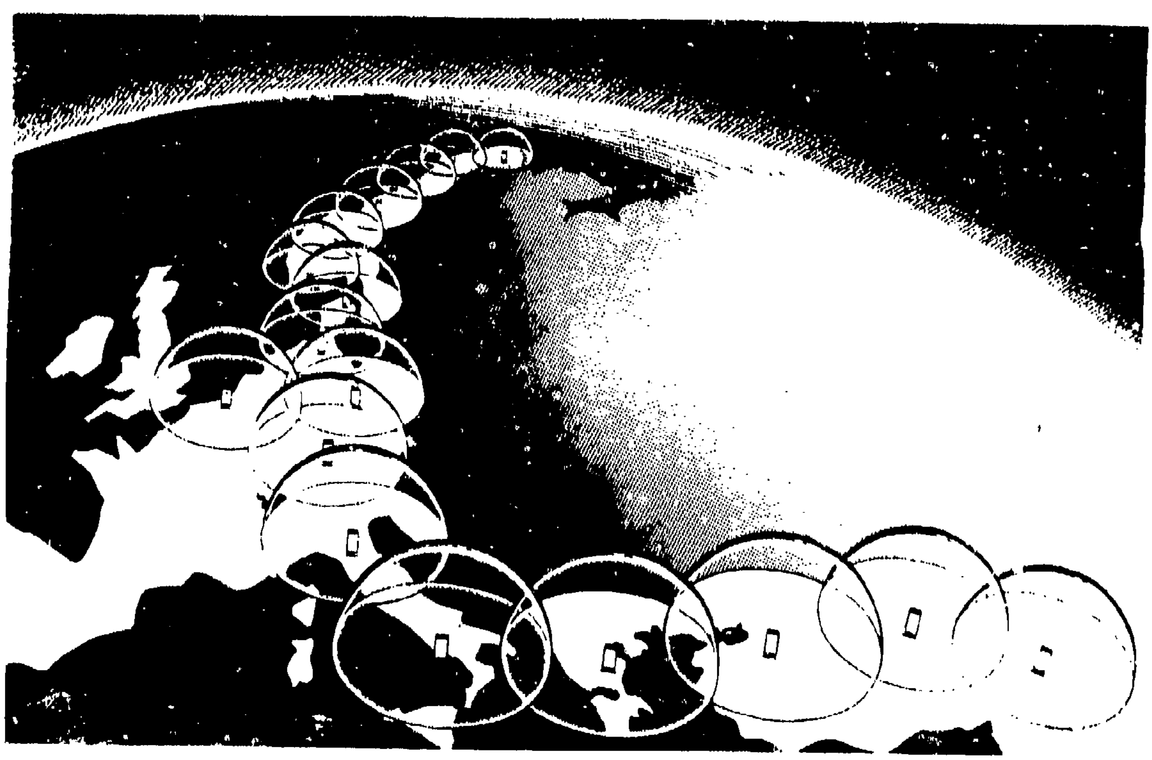


Fig.4 The NADGE concept

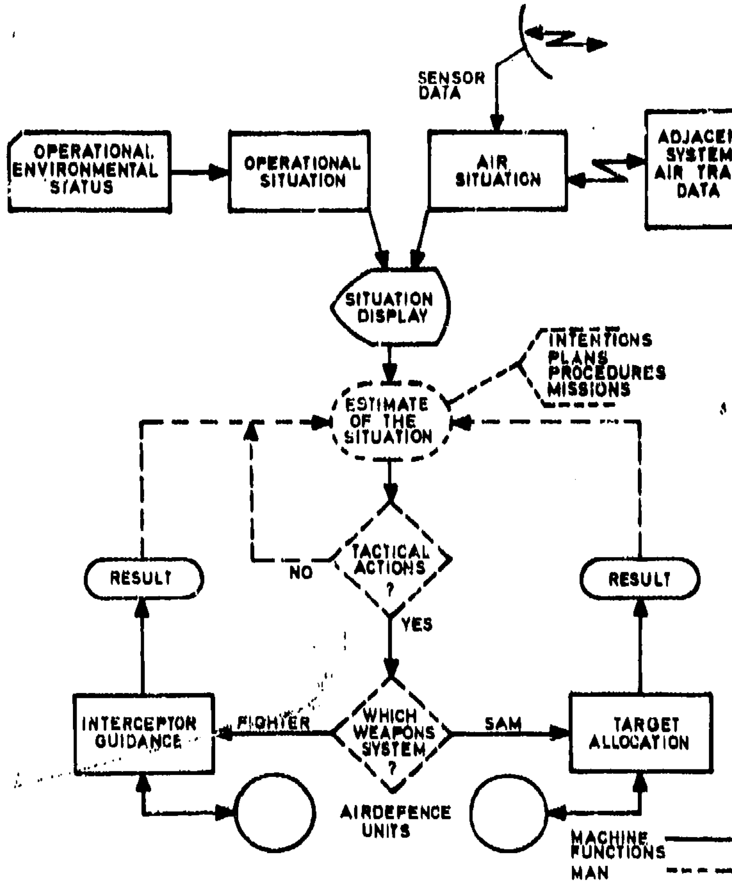


Fig.5 AADGE-site functional flow

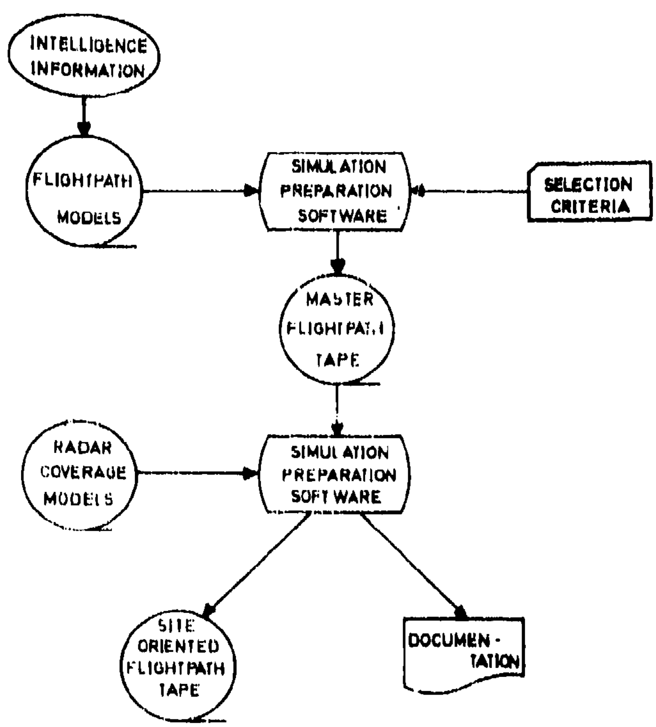


Fig.6 Generation of the simulated air picture

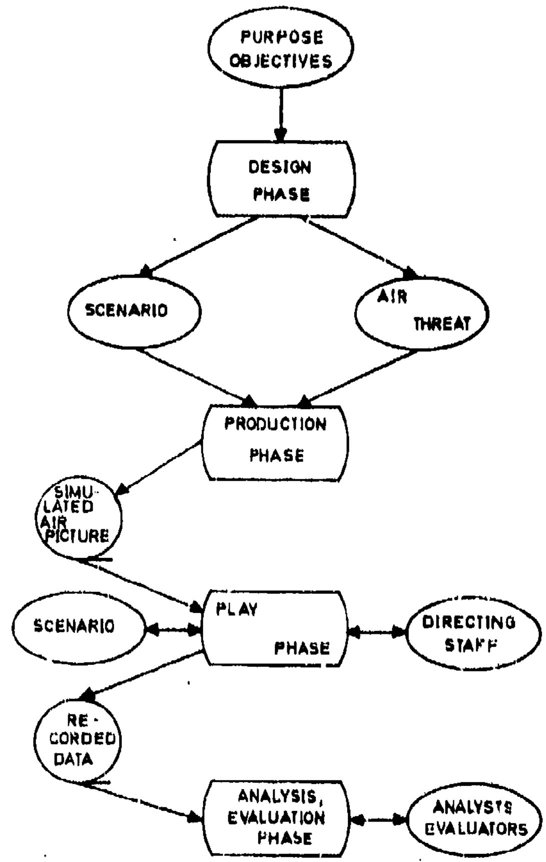


Fig. 7 Phases of air defence war-games

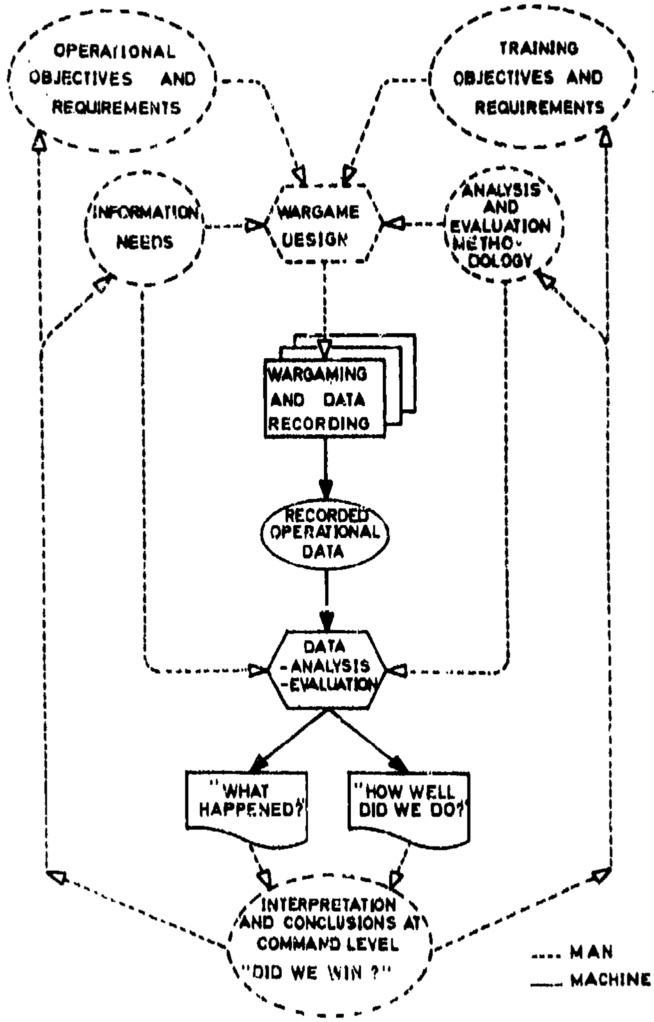


Fig.8 War-gaming overall interrelationship

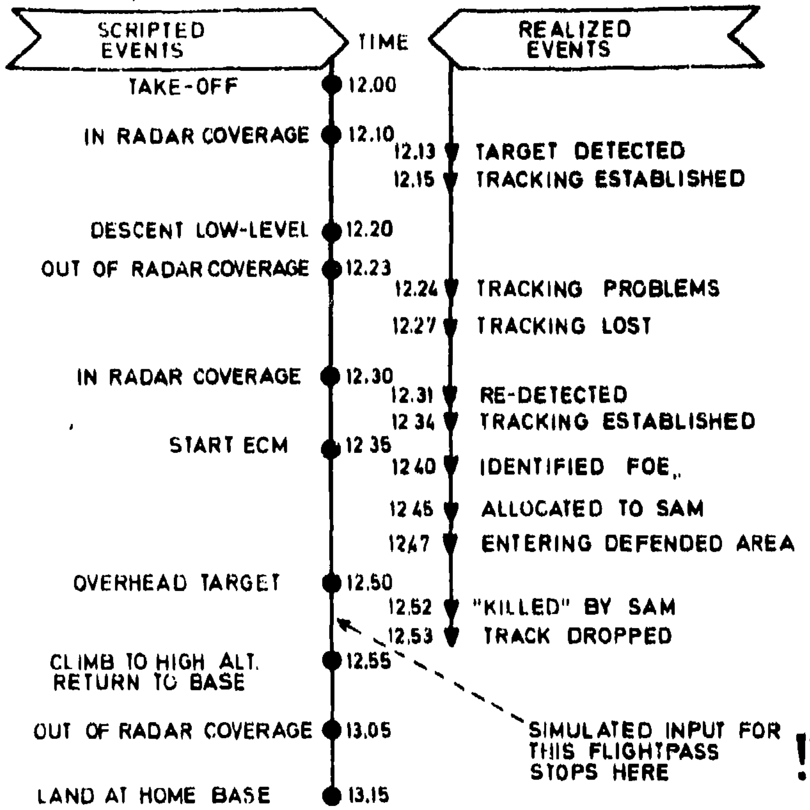


Fig.9 Analysis process in principle
(Example related to an individual flight path)

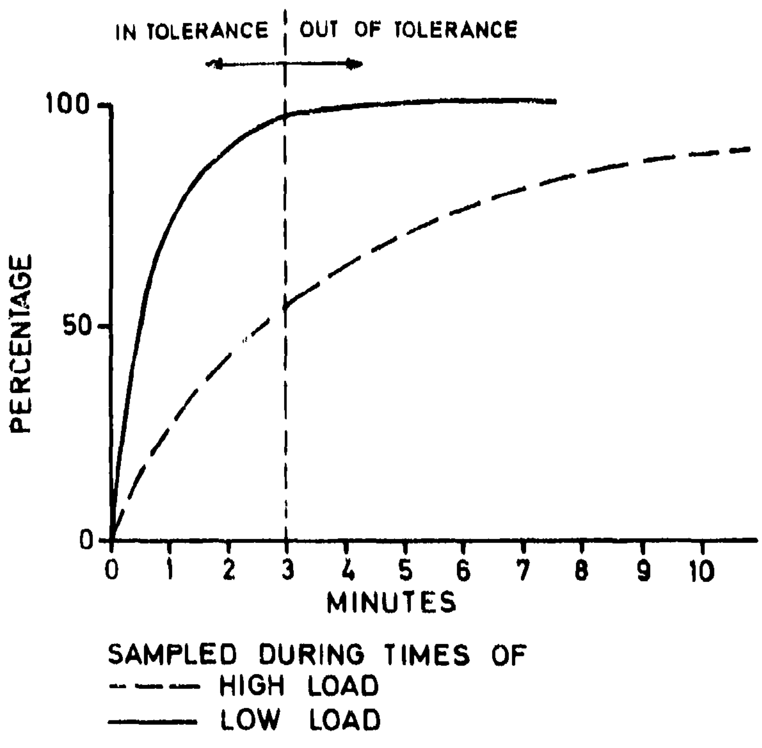


Fig.10 Example of analysis results:
Time to assign initial identification

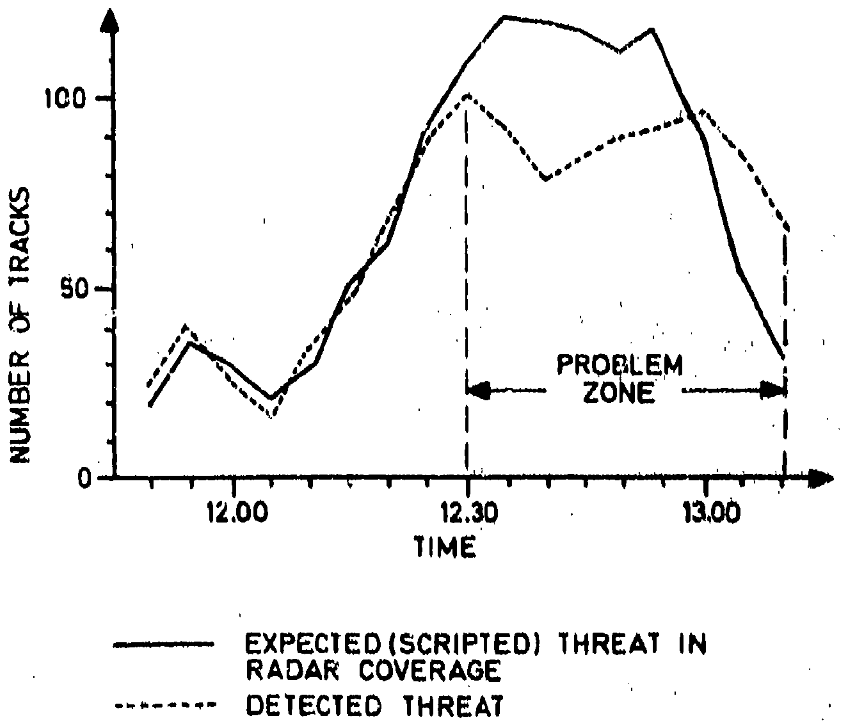


Fig.11 Example of analysis results: Detected versus expected threat

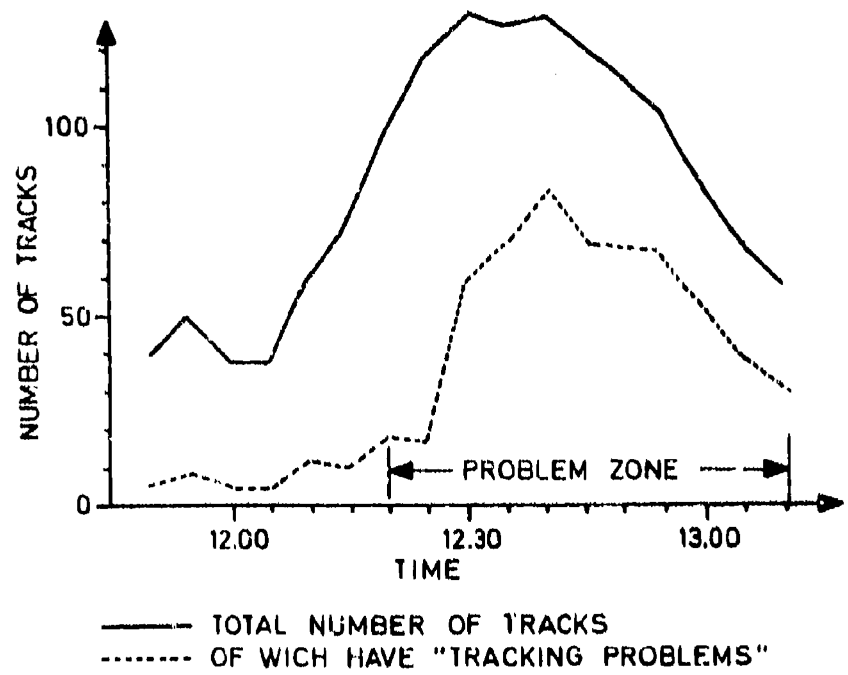


Fig.12 Example of analysis results: Tracking quality versus track load

			RAID #1	#2
	TARGET AREA		AIRBASE XYZ	RADARSITE ABC
THREAT	TIME OVER TARGET		10 : 40/45	11 : 30/35
THREAT	ALTITUDE x 1000 ft		20 - 5 - 20	27 - 3 - 27
THREAT	STRENGTH		14 x 2	12 x 2
THREAT	TYPE A/C		FITTER C	FENCER A
DEFENCE	ENGAGEMENTS * BEFORE * BOMB RELEASE	by SAM	7	2
DEFENCE	ENGAGEMENTS * BEFORE * BOMB RELEASE	by INTERC.	3	0
DEFENCE	ENGAGEMENTS * AFTER * BOMB RELEASE	by SAM	1	4
DEFENCE	ENGAGEMENTS * AFTER * BOMB RELEASE	by INTERC.	2	0
	ATTACKERS REACHING THEIR TARGET		64 %	92 %

Fig.13 Example of analysis results: Tactical actions results

REAL-TIME SIMULATION: AN INDISPENSABLE BUT OVERUSED EVALUATION TECHNIQUE

V. David Hopkin and A.J. McClumpha
RAF Institute of Aviation Medicine
Farnborough, Hampshire, U.K.

SUMMARY

Although real-time simulation can gather certain types of evidence which can be obtained in no other way, it cannot validly be applied to numerous problems in large man-machine systems. Real-time simulation can be viewed as one of several techniques in a hierarchy: the simplest techniques use paper and pencil methods and the most elaborate require real-life operational systems. The existence of large and expensive real-time simulation facilities has helped to promote their overuse. The paper appraises real-time simulation as a technique, with particular emphasis on its limitations.

1. HISTORICAL BACKGROUND

Real-time simulation has become indispensable in the development of complex operational systems. This paper discusses real-time simulation as a technique, drawing examples mainly from air traffic control and air defence systems in the United Kingdom.

Real-time simulation in its present form originated in simulations of aspects of air defence systems during the Second World War (Mackworth, 1950). In these studies, many techniques which are still current were first developed, and attempts were made to explain the findings from real-time simulations in terms of psychological theories of the day, in order to establish their generality and permit their extrapolation.

These early attempts at real-time simulation marked a change in research philosophy. Before them, measures of man-machine systems, using techniques such as time and motion study, sought to increase output rather than to assess the effects of the system on the man, but in these early attempts, man began to be treated as an element or component of the system. It became apparent that the effectiveness of any complex system depended on characteristics of its operators as well as on characteristics of the system itself. The pioneering work of Craik (1945) and of Hick (1947) on the performance characteristics of the operator began the task of expressing human characteristics in mathematical or engineering terms compatible with those used to specify other system components and their functions. This approach encouraged the use of real-time simulation which had the advantage of being able to integrate man and machine and measure them together under rigorously controlled experimental conditions.

These first attempts to interpret the findings from real-time simulations of air defence or air traffic control systems in terms of psychological theory were never totally successful, even though the rationale for trying to do so remained attractive. Several explanations can be offered in retrospect:

1. the theories were wrong;

2. the concepts had limited applicability;

3. real-time simulation was not an appropriate technique;

4. there was too large a discrepancy between the real-time simulation and the laboratory experiments from which the theories originated.

The paucity of alternative techniques and the apparent success of real-time simulation perhaps made inevitable the uncritical over-extension of real-time simulation as a technique.

As real-time simulation became entrenched, specially devised simulation complexes for air defence or air traffic control systems were built. Many of these have been described by Parsons (1972). Their construction and maintenance were expensive, and each represented a major commitment of resources which had to be justified by high utilization. This had two consequences. Firstly, the simulation facility, because it was available, was sometimes used to study questions although the applicability of real-time simulation as a technique seemed dubious. Secondly, the questions to be studied were modified until they fitted the real-time simulation facility.

2. THE DIVERSITY OF REAL-TIME SIMULATION

The range of themes which real-time simulation studies of air traffic control systems in the United Kingdom have considered is illustrated in the following list of headings and examples. An examination of real-time simulation studies of aspects of air defence systems would produce a comparable list. It seems unlikely that the technique of real-time simulation could be so robust that it is equally suited to all these themes.

1. Major Re-structuring of an Air Traffic Control Region. This involves re-casting the air traffic control methods, facilities and procedures within a region. An example is the comparative evaluation of the four possible sites proposed a few years ago for a third London Airport (Ward-Hunt et al., 1970).

2. Revised Divisions of Airspace. Simulation studies may seek to explore all the effects of proposed changes, or be concerned only with their consequences for a designated region or sector. Examples are the specification of the optimum geographical region to be covered from a control centre in relation to the needs of adjacent sectors (George et al., 1971), and the effects of changes in sector boundaries on the control of

traffic within a sector (Crompton & Hopkin, 1975).

3. Co-ordination and Liaison. These factors can be greatly affected by proposed changes, and may ultimately determine their practicability. One simulation study was concerned with a requirement to interweave crossing traffic through the flow of aircraft along an airway (Thayer et al., 1973).

4. The Allocation of Tasks and Responsibilities. These topics are linked to manning levels, the grouping of tasks and the possible amalgamation of functions. One example compared alternative air traffic control procedures and divisions of responsibility to facilitate the training of military student pilots (Thayer et al., 1972). A second example considered the height level at which air traffic control responsibilities should pass from one controller to another (George et al., 1972).

5. The Provision of Computer Assistance. An aid intended for general application may have such wide and diverse implications that they have to be studied by a series of related simulations. An example concerns the benefits of radar data processing. In studying this, basic data were collected first (Crompton et al., 1974), and then civil (Webber et al., 1976), and military (Churchill et al., 1977) applications were examined separately.

6. The Improvement of Traffic Handling Capacity or Safety. The main purpose of an aid may be specific; if so, it must be evaluated accordingly. One study evaluated an auto-alert facility to indicate whenever an aircraft is straying from its planned flight path (George et al., 1973). Two studies of computer-assisted approach sequencing of aircraft on final approach to a single runway (Fearn & Hopkin, 1975) or to parallel runways (Dowsett et al., 1977) constitute a further example.

7. Feasibility Studies. In these, the simulation exercises do not follow a fixed experimental protocol, but evolve in order to explore problems as they are identified. The air traffic control problems of a group of adjacent control sectors have been examined in this way (Fearn et al., 1973).

8. The Evaluation of Technological Innovations. Often these were not devised originally for air traffic control, but an application of them to air traffic control is sought. An example is the use of light emitting diodes in a distance from touchdown indicator (Cooke et al., 1977). A further example, the subject of numerous simulations, concerns the coding of air traffic control computer generated information in colour (Hopkin, 1977).

3. REAL-TIME SIMULATION IN RELATION TO OTHER TECHNIQUES

Real-time simulation belongs to a hierarchy of techniques for the study of man-machine systems. They can range from studies with very simple apparatus to measures of real-life systems.

Studies with simple apparatus, or even with paper and pencil, are intended to explore and define general or specific human abilities and limitations. They permit the examination of a few variables at a time, so that their effects on performance and the interactions between them can be established. Such studies may suggest whether abilities could be improved or limitations overcome. They can provide evidence on tasks that are suitable for study by real-time simulation, on appropriate levels of difficulty, and on measurable aspects of performance.

The next logical step is to conduct more extensive investigations to establish whether the findings can validly be extrapolated from static to dynamic conditions. Controlled dynamic laboratory experiments can help to define the most critical events and circumstances and indicate the probable capability of the man to do the tasks envisaged in the real-time simulation. Without such experiments, the validity of the findings of real-time simulation may be disputed.

As the complexity of dynamic experiments increases, they normally incorporate more of the features of real-time simulation, such as representative tasks, realistic workspaces, and physical environmental conditions. There is no clear dividing line between a complex dynamic experiment and a simple real-time simulation. Criteria for differentiating between them include strict adherence to an experimental design with full control over the variables, and the extent to which all relevant features of the real-life task have been replicated.

Real-time simulation, the main theme of this paper, should be preceded by static and dynamic experimental studies. It should be followed by verification of its findings in real-life. Comprehensive and systematic measures are difficult to obtain in real-life. Real-life data are seldom as structured and comprehensive as data from real-time simulations. A fundamental weakness of real-time simulation is that ultimately the credibility of its findings depends on real-life verification which is rarely attempted and may be impractical.

4. REAL-TIME SIMULATION AS AN INVESTIGATIVE TECHNIQUE

4.1. Detailed Planning

To be effective, real-time simulation must not only be used correctly in relation to other techniques but must also be introduced at an appropriate stage in the system development (Meister & Rabideau, 1965). One major benefit of real-time simulation, an incidental product of it which seems to be consistently underestimated, is that in order to plan and conduct the simulation it is essential to specify thoroughly and in detail exactly how the system will function. Without real-time simulation, this may never be done. The construction of samples for real-time simulation entails clarification of the problems to be studied, and of the methods and measures to be employed. The functioning of the system has to be envisaged in

detail before the hardware and software for real-time simulation can be specified. As a result, before the real-time simulation begins, many of the questions originally posed will have been partly answered. The conduct of the real-time simulation often puts quantitative values on these more intuitive answers. The fact that the process of real-time simulation demands this preliminary thinking is a major advantage.

4.2. System Inputs and Outputs

Real-time simulation is generally system orientated. Input variables typically controlled are the numbers of aircraft or targets. Measures attempt to relate variations in these input numbers to measured outputs from the system. In order to gain an understanding of how the system functions, it is necessary to control inputs, define outputs and explore their interactions carefully. A recurring finding from real-time simulations is that attributes of the operator, as distinct from aspects of the system, greatly affect system outputs through operator processing (Older & Cameron, 1972). In any event, real-time simulation must take account of attributes of the operator as well as those of the system. Although questions can be posed in terms of targets that an air defence system can handle in a given time or the maximum rate of aircraft movements per hour that an air traffic control system can deal with, it does not follow that real-time simulation can provide a valid answer to such questions or even that a sensible answer to such questions exists. A potential advantage of real-time simulation as a technique is that it does not have to be exclusively system orientated, though it usually is. The performance of specific tasks can be measured not only in relation to system variables, but also in relation to the demands which they impose on the operator and to individual differences between operators.

In a typical real-time simulation, the inputs to the system are specified exactly, the consequences of specified changes in them are quantified, and the simulation design is derived from the findings of preliminary laboratory experiments. This approach is sensible, and indeed is the best one for many purposes of real-time simulation. But it is not the only one, because real-time simulations can be exploratory. A useful role for real-time simulation is to try out new ideas, with sufficient realism to establish whether they are worth serious consideration and further development.

4.3. Comparative Assessments

Once it has been established that a new idea is feasible, then real-time simulation can be used to make comparisons. Often the essential evidence is not that a new idea is practical but that it is better than what it would replace (Orr & Hopkin, 1972). There are difficulties in making this kind of comparison.

When real-time simulation is used to compare a new and existing idea, the expected advantages of the new idea are already, to some extent, known, and the real-time simulation is designed to demonstrate these expected advantages. The disadvantages of the new idea have never been considered with equivalent thoroughness, and therefore simulation may fail to reveal them.

As a general principle any change, particularly in a system context, brings both advantages and disadvantages. Both should receive equal attention in a comparative simulation (Hopkin, 1970). A major benefit of real-time simulation as a technique is that it allows in principle the impartial investigation of advantages and disadvantages.

A further source of bias can arise when real-time simulation is used to compare automated and manual methods of performing functions. There may be the implicit assumption that the automated method must be better. As a result, if the automated method proves inferior to the manual one, much effort is expended on improving it until it is as good as or better than the manual one, whereas if the automated method is already superior to the manual one, comparable effort is not expended on improving the manual method until it is as good as or better than the automated one. An optimised machine is compared with a non-optimised man.

Normally any change affects the kinds of error which can occur. A main reason for replacing equipment may be the removal of unacceptable errors associated with it. However, whatever is introduced in its stead will have its own characteristic errors. For example, the replacement of spoken messages by transponded data which appear on displays replaces phonetic confusions with visual misreadings. Real-time simulation must therefore seek to establish which errors actually occur. Further current examples concern the errors introduced by colour coding of displayed information (Hopkin, 1977), and the errors which automated speech synthesis and speech recognition may generate (Connolly, 1978).

4.4. Choice of Subjects

The choice of subjects can have a crucial influence on the findings of real-time simulation. One competent operator participating in a simulation may be sufficient to show that an idea is feasible. Usually the aims of real-time simulation are more ambitious and include the assessment of individual differences between operators by representative sampling. The extent to which those chosen to participate are truly representative influences the findings.

One solution is to employ subjects whose main job is to participate in simulations. Their performance and opinions may be helpful and full of insights for simulation purposes, but biased because of their familiarity with simulation. An alternative solution is to employ as participants in the simulation those who fulfil an equivalent role in existing systems. Using their specialist knowledge, they can point to the aspects of real-life which have been inadequately replicated in the simulation and which may therefore render the findings invalid. Their familiarity with the equivalent functions in real-life may bias their performance and opinions. Further difficulties arise in choosing subjects for comparative simulation studies, where the new and familiar are compared. Experienced subjects are already practised on the familiar equipment far more than they can be on the new, which introduces a bias. Naive subjects, for whom the items being compared are both new, may never become fully proficient within the practical time limits of real-time simulation. Furthermore, the training methods are known for the familiar equipment but have to be devised for the new.

5. REAL-TIME SIMULATION AND CURRENT HUMAN FACTORS PROBLEMS

5.1. The Introduction of Computer Assistance

A common application of real-time simulation is to examine various forms of computer assistance. As automation progresses, the list of functions which can be considered in terms of whether they should be performed by man or by machine increases. This is a matter of technical progress and not of human factors (Benoit, 1976). A consequence is that the man may be left with the tasks which have proved difficult to automate rather than those for which he is particularly suited. For example, he tends to be cast in monitoring roles where he is inefficient, or in supervisory roles which he has difficulty in fulfilling in highly automated systems. Real-time simulation can establish whether the man will actually be able to fulfil the roles assigned to him (Hopkin, 1976). It can also be used to examine the practical skills which he will need (Whitfield & Stammers, 1978).

5.2. The Measurement of System Capacity

Real-time simulation is often used to try and assess system capacity (Parsons, 1972). The capacity of the system relates to the system as a whole, but the findings of a real-time simulation are influenced by the behaviour of the individual operators participating in it. Therefore this technique cannot provide answers to questions of system capacity which are divorced from characteristics of the operators. Real-time simulation can never reproduce faithfully every aspect of real-life: for instance, the emotional climate under which the work is done and the state of learning and proficiency are different. The effects of such operator characteristics on system capacity are uncertain. In simulation it is necessary to retain some control over the permitted sources of variance in order to gather meaningful quantitative data. To the operator, this constraint often engenders an artificial smoothness and predictability in the simulation exercises, with indeterminate consequences for system capacity measures.

5.3. Workload

There is a great demand in air defence, air traffic control and other systems to assess operator workload, but it is difficult to do so validly using real-time simulation. Confusion often arises if workload is equated with the demands which the tasks impose upon the operator, since workload depends also on his individual characteristics. Workload is a multifaceted concept, affected by an operator's knowledge, experience, proficiency, attitudes, training, aptitudes, understanding, age, etc (Moray, 1979). Various attempts to measure workload using real-time simulation have been made in air traffic control (Ergonomics, 1971). These generally treated workload as a single measurable dimension, which it is not (Moray, 1979). Assessments which claim to measure workload along a single dimension should therefore be treated with scepticism. The appraisal of workload, insofar as it is possible, almost certainly requires numerous kinds of measure. Real-time simulation can however be used to establish task demands, and assessments may be made of whether these demands are excessive for particular operators. Task demands should not be equated with workload.

5.4. Stress

Real-time simulation has also been employed to assess stress (Crump, 1979). Various studies have tried behavioural, physiological, biochemical, or subjective measures. The susceptibility to stress may be related to personality characteristics which cannot be expressed by system measures but only by assessments of the individual. Some stress-related effects of the system on the man are long term and beyond the scope of real-time simulation. Insofar as stress is construed as a product of excessive demands on the man, real-time simulation may be used to assess the effects of certain proposed system changes on stress indirectly in terms of task demands.

5.5. Boredom

Boredom shows every sign of becoming a more serious problem in future systems as an unwanted incidental consequence of further automated assistance. Its causes and effects are not well known (Hopkin, 1979). There is therefore a need to develop means for studying it in order to assess its consequences and perhaps to prevent it. Real-time simulation seems unlikely to be a suitable technique. The participants in real-time simulations are placed in an unfamiliar and intriguing environment, for a limited time with short work periods; such factors mitigate against the occurrence of boredom. If, nevertheless, boredom occurs in real-time simulation, it may merely end the willing collaboration of the participants.

5.6. Attitudes

Attitudes towards tasks may also be measured in real-time simulation. Such measures have to be treated with some caution since the attitudes developed during the brief exposure to a new task in real-time simulation may not be representative of the attitudes to the real-life task after full task proficiency has been developed and the novelty of the simulation has worn off. Nevertheless, subjective assessments of the acceptability of the task may be obtained during real-time simulation. Real-time simulation can be used far more than it has been to explore what attributes of tasks, equipment and environmental conditions are acceptable to users and engender favourable attitudes (Hopkin, 1975). However, its relevance to the study of attitude formation has limits: peer pressure, for example, may strongly influence attitudes but not be amenable to study by real-time simulation methods.

6. CONCLUSIONS

Although in this paper real-time simulation has been appraised in relation to large man-machine systems, and particularly to air traffic control systems, most of the comments made appear to be true for real-time simulation in general and therefore may remain valid in other contexts.

Real-time simulation has been inadequately integrated with other available techniques, with theoretical concepts on which it could be based, with exploratory studies which should precede it, and with

verifications which should follow it. Sometimes it seems to have been used not because it is the best method, but simply because it was available. The diversity of its applications suggests that its usage has been somewhat uncritical; this diversity also points to great (though misplaced) faith in real-time simulation as a technique. The tendency to adopt real-time simulation as a technique for tackling almost every problem cannot be justified on scientific grounds nor in relation to the findings which have been obtained hitherto by using it.

Real-time simulation should never be an end in itself; its value cannot be judged in isolation. The purpose of simulation is to gain insight into the functions of a proposed real-life system or to try and replicate aspects of real-life in order to study them where variables can be properly controlled. The findings from any real-time simulation are therefore of limited interest in their own right; their interest depends partly on showing their relevance to real-life systems. Real-time simulation can never replicate exactly every relevant aspect of real-life.

It is doubtful if some topics, such as system capacity and workload, can be studied validly by real-time simulation. Other topics, such as peer pressure and boredom, seem beyond its scope altogether.

Real-time simulation can nevertheless be an effective aid. Some kinds of information can be obtained by no other means. It can verify the suitability of physical environments and workspaces. It can establish the intrinsic feasibility of new ideas and methods, and assist them to evolve. When properly used, it can provide descriptions, insights, and explanations of how a system is functioning because variables can be defined and isolated so that their direct effects and their interactions can be disentangled. It can be used to explore, and to make comparisons. It can be used to correct inherent sources of bias in evaluations, and to reveal the kinds of error to be expected.

The above reasons lead to the general conclusion that as a technique real-time simulation is both indispensable and overused.

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DESIGN AND SIMULATION OF A C³-SYSTEM FOR SURVEILLANCE PURPOSES

Franz Herzmann, Helmut Sanders

Elektronik System Gesellschaft,
Vogelweideplatz 9, 8000 München 80, F.R. Germany

SUMMARY

The autonomous operation of several air defence weapon systems often leads to a simultaneous multiple fight against the same target, which in most cases effects an overkill. Coordination of target allocation multiplies the efficiency of air defence systems. For the fire coordination this presupposes the unambiguous knowledge of the air situation. This air situation is acquired by a surveillance network consisting of up to 20 mobile radar posts. Communication between the posts in a meshed network requires the solution of control problems, such as data correlation and reduction, and feedback filtering. If communication is performed by HF-data links, like in the system described, radio transmission problems arise additionally. Radio range, transmission reliability, and channel coding for the correction of corrupted data become an important factor for system operation. For the purpose of obtaining both , a complete radar coverage of the surveillance area and a multiple meshed network, the determination of the radar post locations has to consider radio and radar ranges near the earth's surface with respect to the topographical environment. For avoiding mutual jamming, the radio and radar frequencies of each post have to be coordinated with those of all posts within radio or radar range, respectively. Tracking algorithms, performed by the tracking computer at each post provide for automatic track initiation and tracking even of jammers. Their design has to consider the reliability of radar-derived data, that clutter and hostile radar jamming do not confuse target tracks. In order not to restrict the high mobility of the radar posts, the algorithms have to cope with network failures and reconfigurations. The operation of the surveillance network and of the weapon systems, including the coordination of their allocation, raises a lot of C³-problems. This paper deals with the problems themselves and with an approach to their solution as follows:

- modelling of air situations, radar sensor features, weapon system features, and imitation of data links
- design of tracking and allocation algorithms
- simulation of network operation, accompanied by iterative improvements of the algorithms
- simulation of weapon system operation, including coordination of target allocation
- testing the system performance by means of radar-derived data.

The approach described has enabled a cost-effective solution of the problems indicated. The development risk has been reduced to a level at which implementation of the system is guaranteed.

1. SYSTEM CONFIGURATION

The radar network consists of 10 to 20 mobile posts with overlapping radar coverages (Fig. 1) to attain a good system detection probability for extremely low-flying aircraft at terrain following or terrain avoidance flight profiles. The variable positions of the posts will be primarily chosen with the aim of a complete radar coverage of the entire area of interest with special regard to lowest level flight profiles /1/.

Since the network requires no central coordinating and processing station, a broad spectrum of possible system configurations can be handled. In order to avoid restrictions on system flexibility, and to be resistant against failures of radar posts, neighbouring posts are interconnected by HF-data links (Fig. 2). Tracking is performed identically in each radar post. Each radar post has to accomplish

- target detection
- data extraction
- data correlation
- track determination
- data distribution and
- display of air situation

According to these tasks, each post is equipped with (Fig. 3)

- a radar sensor including a data extractor
- a communication set (transmitter/receivers, coding/decoding units)
- a tracking computer (TC)
- a display unit

Computed track information is transmitted and simultaneously displayed on a digital display unit. This enables the operator to check tracking results and, on demand, to classify targets (friend, unknown, mass approach, jammer). Due to the requirement for target allocation to weapon systems, tracks must have a maximum life time and minimum data ageing. In the best case, the data age is less than 1 second. The track update rate varies between 1 to 4 messages every 3 seconds.

Because the track information at every post reflects the same air situation, users can tune their receivers to any post which is most convenient to them.

2. PLANNING OF SYSTEM OPERATION

The EDP-based procedures for operational planning of the surveillance system aim at adapting the planning methods to the mobility of the surveillance network.

New planning procedures must mainly be employed for the following tasks:

- radar post location planning (radar coverages)
- network configuration planning (radio links)
- frequency coordination (radio and radar)

2.1 Radar Post Location Planning

The objective of sensor position planning is to determine those locations for the individual radar posts of the network which enable a maximum complete total surveillance. The principle of generating radar acquisition diagrams is to determine the respective radar lines of sight as a function of an assumed target altitude for the total 360° scan (Fig. 4).

Up to now, radar acquisition diagrams were generated manually with the help of terrain profiles obtained from maps. For the purpose of obtaining a result in this procedure in infinite time, the angular resolution was chosen to be relatively coarse (Fig. 5).

EDP-based procedures rely on a digital terrain data base and are capable of generating radar acquisition diagrams of a much better resolution and within considerably shorter time.

The following aspects have to be clarified in the course of simulation activities for EDP-based sensor position planning:

- optimum structure of the terrain data base. At a coordinate resolution of 250 m, and at an elevation resolution of 1 m, the data base contains about 1 M byte per area of 100 km x 100 km.

- optimum procedure for determining new positions for the radar network within a short time.

- suitable manner of representation of the acquisition diagrams, especially of the representation of the total network coverage.

2.2 Network Configuration Planning

Keeping the radar post on the locations determined in the preceding workstep, network communication planning is required to obtain the best possible communication network. Its objective is to determine multiple redundant radio links between neighbouring posts, regarding the following conditions:

- each post transmits information at a single frequency to neighbouring posts, with omnidirectional characteristics

- each post receives up to three neighbouring posts on three receivers; the reception of 2 neighbouring posts shall be possible in any case.

The procedure of network configuration planning provides for an initial classification of all possible radio links between neighbouring posts with regard to their transmission performance (Fig. 6 and Fig. 7).

Essential parameters regarding the performance of a radio transmission path are - in addition to the equipment performance characteristics - the distance and the terrain profile between the posts. The influence of the terrain is covered in an approximation solution with the help of the "shadowing height". The "shadowing height" will be determined via the digital terrain model.

Radio links to be provided will be selected according to the following approach:

- in an initial step, those posts are selected, to which only two linking possibilities with neighbouring posts exist. Depending on the case, also radio links of lower quality have to be used in connection with these posts.

- in step no. 2, additional radio links with good transmission performance are selected for each post.

- in step no. 3, the network configuration is completed by the selection of additionally possible radio links, with a limit of three receiving channels for each post. This completion effort may contain unidirectional links.

3. COMMUNICATION

Data communication is realised by transmitting track data omnidirectionally to every other radar post within radio range. Three receivers at each post permit the configuration of a multiple-meshed network with the advantage of multiple redundant data transmission. In most cases, data links between two posts are bidirectional. A unidirectional data link is given, if at one of two communicating posts all receivers are tuned to other posts or if radio disturbances of the received frequency are present.

The tracking computer distinguishes between:

- Target reports from its radar
- Track messages containing a preliminary track number
- Track messages containing a final track number.

Target reports contain the following:

- target position
- target altitude (3D-radar only)
- date of measurement
- type of target.

Track messages contain additionally:

- track number (preliminary of final)
- target velocity
- track quality.

Target reports themselves will not be distributed externally but they trigger the distribution of track messages. Track messages containing a preliminary track number are distributed as quickly as possible to all posts in order to shorten the preliminary tracking phase (see 4.1.5).

Figure 8 shows the radar plots derived from four radars, detecting three targets. Each radar/tracking post has to process all radar plots from its own radar and all track messages from the three other posts.

Regarding the data reduction task, it has to be pointed out that each post has 4 data input channels (Fig. 3), but only one output channel with a capacity equal to each input channel. Therefore, on an average only a quarter of all reported massages can be relayed. For reducing the quantity of messages circulating in the network, each post forwards messages only, if the corresponding registered track is being updated or if its track number is being changed by that message. In this way, feedbacks are recognized and eliminated.

The transmission capacity of the specified hardware limits the message rate per target. Therefore only those messages are forwarded that prolong a track by at least k seconds (k = 1 s/message rate) with respect to the last message. The forwarded message is updated and contains the most recent smoothed track data. In order to reduce ageing of messages on their way through the network, radar returns get priority above messages received via data link in triggering new messages (Fig. 9). Fortunately, the rotation rate of most of the radar antennas in the system is twice of the message rate required for each target. Consequently, each radar, which detects a target causes the TC to trigger its message clearance at every other antenna rotation. So, ageing of messages occurs almost exclusively at stations which do not detect the target concerned. In the case that a target return is missed, the next available message - from radar or via data link - will trigger the transmission of the new message.

4. SIMULATION OF THE SURVEILLANCE NETWORK

In multiple radar networks, where the dispersion of the radar posts is dense with respect to their individual radar coverages, an incoming target may often be detected be several radar sensors almost simultaneously. When the network consists of radar posts with collocated tracking facilities of equal authority in order not to require a central processing station, while the capacity of the data links and of the track data processors are limited, track initiation, tracking and management cannot be performed effectively by conventional methods.

4.1 Tracking Algorithms

Tracking is realised simultaneously in each radar post, even if its own sensor does not detect the target. Tracking algorithms provide for a unique track with an unambiguous track number at all posts for every target entering into the system surveillance coverage, even if it is detected by several radars simultaneously. The system track number is kept unambiguous even if target trajectories are crossing. Tracking of target formations is limited only by the resolution capabilities of the radars. In the presence of jammers, their bearings will be tracked and their positions will be triangulated. Fig. 10 shows the combined evaluation of bearings, plots and tracks.

4.1.1 Data Processing

Target data delivered by radar and track messages, which have been received from neigh-

bouring posts via data link have quite different features. Radar-derived data are most recent, but they contain less information (Fig. 11) and are less reliable than track messages, which are already filtered. For evaluating both kinds of information in an optimum way, two separate filters are implemented in the tracking computer.

The plot filter correlates exclusively target reports derived from the radar of the post concerned, and initiates and maintains sensor tracks by alpha/beta-filtering.

All sensor tracks of one single post form the sensor-derived air situation of this post. The total of all tracks of the surveillance network forms the system-derived air situation. Sensor track messages contain the same amount of information as system track messages.

The track filter correlates both, sensor track data, and system track data received via data link, with the registered system track data to update the system track. This is performed by an alpha/beta-filter with dynamic coefficients depending on the track quality. Parameters for the determination of the track quality are:

- the age of a track,
- the track status (preliminary or confirmed),
- the amount of associated and correlated target reports from the collocated radar,
- the amount of correlated track messages received via data link,
- the time elapsed since the last updating.

There are many advantages in filtering radar-derived data separately from the other system track data received via data link /4/, /5/.

Firstly, all radar-derived data from one post have a constant systematic bias. By correlating only target data from the same radar the bias does not effect on plot associations. This increases the probability of a correct association of successive target reports.

Secondly, the constant bias and the adequate sampling time of the radar antenna improve the computation of the target velocity. If track positions received via data link were utilized for the velocity computation instead, two problems would arise:

- different biases of detecting radars would run up,

- by utilization of messages one shortly after the other, the radar measurement error can be of the same magnitude or greater than the distance, the target has flown in the meantime.

Both problems result in an error of the computed target velocity followed probably by a wrong association.

Both advantages, i.e. correct associations coupled with improved velocity computations lead to a smoothed track of good quality and high reliability.

4.1.2 Plot Association

Every target detection by radar is reported to the tracking computer which tries to allocate the target report to a suitable existing track (Fig. 12). For the association of radar plots to an existing sensor track, positions, altitudes, velocities and measurement dates are checked. Information about the target's identity /2/3/ is compared only to disentangled track confusion due to crossing trajectories etc. If the reported target is positioned within the expected window of the predicted registered track, it will be associated. If there is no correlation between the reported radar plot and any registered target track, the tracking computer (TC) tries to initiate a new track. It stores the reported plot data into a track register (TR) (Fig. 13) for a possible association with a plot, expected during the next rotation of the radar antenna. In the absence of the expected second plot report, the plot is assumed to be a false target report, and its data in the TR will be eliminated. If the used radars have a small detection probability, a third antenna rotation can be tolerated for a second detection of the target. If the radar does report suitable plots in consecutive antenna periods, they will be joined to a potential track.

After the association of three plots within three consecutive antenna turnarounds, a track message with a preliminary track number is externally distributed initially. For each association check, the plot data derived from a 2D-radar will be slant range corrected. The slant range error is the difference between the measured slant range to the target and the length of the line of sight projection onto that horizontal plane, which contains the radar's position (Fig. 14). At large elevation angles, the slant range error may amount to 30 % of the slant range. If height information is missing, the measured slant range must be interpreted as the horizontal range. This may result in shifts of the computed target position and in bendings of the track. If the slant range error is large enough to effect association, a new track will be initiated, so that the same target is tracked twice. For slant range correction, heigth information from any 3D-radar or SSR-information can be used.

4.1.3 Track Association

Each tracking facility, which receives a track message, checks whether that track is associable to a track, which is already stored in its TR (Fig. 15). At first it looks

for the reported track number. If the TC finds it in its TR, it checks whether the reported target belongs to the stored track. If the TC cannot find the same track number, or if there is no correlation between the tracks with the same track number, it checks all registered tracks to correlate the received track information with the most suitable track. In order to enhance the survivability of confirmed tracks, they are preferred to preliminary tracks for the association. If there is no correlation even to a preliminary track, the received track message is added to the other tracks in the TR and forwarded via data link to all neighbouring posts. In the case of an association of two tracks with different track numbers, a track number harmonization procedure provides for an unambiguous final track number in all tracking posts.

Associated track data will be used to update the appropriate track, provided that the received target information is more recent than the stored track information. Older messages will be disregarded. After updating, a track message containing the most recent track data is transmitted to neighbouring posts in accordance with the track reporting procedure (see 3).

Tracks will be carried on in all posts as long as the target is detected by at least one radar. After a target is missed for a fixed time period, the track will be terminated (Fig. 13). This time period is determined by the slowest antenna turn rate of the radars used, in order to give the collocated TC a chance to continue tracking in spite of missing a target once. It is not expedient to wait any longer for a radar plot, because the prediction quality decreases rapidly and the track-window for the expected plot position would have to be enlarged accordingly. In a dense air situation this increases the probability of a false association.

4.1.4 Jammer Tracking

In the presence of jammers, the radar-derived bearings are tracked automatically. Bearing association and tracking is performed similarly to regular echo target tracking with different parameters. Since all posts distribute their tracked bearings to all other posts, the jammer's position can be determined by intersection calculations (Fig. 10).

Because n bearings can generate max. $\sum_{i=0}^{n-1} i$ intersections, not every intersection represents a jammer, even if only few jammers are present. Ghost targets are eliminated by demanding a minimum of intersections being close together for the definition of one single jammer. Because of inaccurate bearing measurements, intersections can accumulate accidentially at wrong positions. Special methods and algorithms are used to determine the correct jammer position. The calculated jammer positions are evaluated like regular echo target plots for track initiation and tracking. If intersections are located near to a regular target, it is assumed to be a jammer.

4.1.5 Track Number Management

Track number management provides for identical track numbers for every target track in each radar post. It is activated in two cases:

- for harmonizing different track numbers concerning the same preliminary track
- for rechanging final track numbers in a predefined way in all posts if numbers of confirmed tracks have been exchanged by mistake.

Harmonization of Preliminary Track Numbers

Due to the overlapping coverage, many incoming targets are initially detected by several radar sensors at almost the same time. Each radar post, which detects a target three times in subsequent detection cycles, distributes a track message with a preliminary track number. Each post has a specific prefixed pool of track numbers, so preliminary track numbers assigned by different posts are always different.

If a post associates two tracks which are identical but have different preliminary track numbers, the track management elects the smaller number to survive. The track message, which is forwarded contains the most recent track data but the smaller track number.

Depending on the network deployment, a message needs a certain minimum of time to reach all posts. A period of twice of this time (pre-phase period) is sufficient for the harmonization of different track numbers, related to the same target. At the end of this period each message concerning this particular target contains a unique final track number.

Rearranging Ambiguous Final Track Numbers

A puzzling situation arises in every tracking mechanism when targets fly crossing trajectories or when targets split up after flying in close formation. Consequently, track-numbers tend to be swapped (track A, number A and track B, number B change into track A, number B and track B, number A respectively), or track numbers are doubled (two tracks with the same number), or tracks will be doubled (one target, two tracks with two numbers). For restoring the unambiguity of final track numbers, each post induces a harmonizing track management procedure, which rearrange track numbers in a predetermined way.

If the radar accuracy is less than the separation of the targets, neither the radar data extractor nor a human operator can decide, which of the reported radar plots belongs to which target. In view of this fact, targets flying closely together or flying crossing

trajectories are tracked separately with different track numbers, but the unambiguity cannot be guaranteed. This lack is not critical for system operation, since the overriding point for a simultaneous track data processing is that all posts keep the same number for the identical track, even if targets are exchanged. Recognizing this, a very simple changing procedure is chosen to save computing time. Examples of simple changing criteria are as follows:

- the target flying the most Southern track gets the smaller track number,

- if both targets fly at the same latitude, the target flying the most Western track gets the smaller track number.

4.2 Models

4.2.1 Air Situations

In accordance with the demanded system performance, the surveillance network has to cope with more than 100 targets. Most of the targets are assumed to manoeuver with lateral accelerations up to 3 g at speeds of about Mach 1 and at very low altitudes. Aircraft at higher altitudes are assumed to fly at a maximum speed of up to Mach 3. Some of them are friendly, others are of unknown identity. Jammers are of stand-of (SOJ), self-screening (SSJ), and of ecort (ESJ) type. The jammed sector in front of the jamming aircraft can be varied.

Three basic models were developed. In order to simulate a wide spectrum of air situations, each model can be modified in its parameters. In some simulation runs e.g. some targets became jammers, or single targets were substituted by formation flights with various numbers of aircraft.

A fourth air situation model of the STC was tested with regard to its usefulness, but it was proved that it requires less comfortable algorithms than the first three ones.

4.2.2 Radar

In order to detect all targets, in low level flight and in the upper airspace, different types of radar sensors with different performance are combined.

About 3 mobile, 3D-phased array radars are used to survey the whole area of interest. The azimuthal scan is performed mechanically. It has a theoretical range of 100 km, which causes an antenna rotation rate of about 6 r.p.m. The good target resolution of this radar enables the discovery of single aircraft flying in formation with the advantage of a quick and distinct track reaction upon splitting up formations.

Because of the earth's curvature, extreme low-flying targets at distances greater than 40 km are hidden behind the radar horizon. Therefore, additionally, a lot of highly mobile, mechanical scanned, 2D-radars is dispersely located to detect aircraft at terrain following or terrain avoidance flight profiles. These radars are designed especially for lower airspace surveillance within a range of max. 30 km. For clutter suppression a doppler-type radar sensor was chosen with alternate pulse repetition frequencies (p.r.f.) at consecutive antenna rotations. The radar model pays regard to this fact by providing different blind velocity ranges dependent on the p.r.f. The radar antenna rotates at 40 r.p.m. Target resolution and data accuracy are smaller than in the case of the 3D-radar.

Radar-derived false alarm plots, which are uniformly dispersed over the radar surveillance coverage are added to the radar output according to rates stated by the radar manufacturers.

Unfavourable positioning of the mobile radar posts may reduce the acquisition range near the ground to a few kilometers (Fig. 16). This circumstance is considered by modelling different radar coverages varying in height level and azimuth. A digital model of the area of interest can be used to compute exact radar coverages (see 2.1).

4.3 Simulation Steps

The simulation was performed in three steps. The first step was to prove the ability of the algorithms to track targets of modelled relevant air situations. The second step proves the realtime capability of the tracking algorithms implemented in a process computer. Finally, models of the air situations and of the features of the radars are replaced by real air situations acquired by radar sensors under real conditions.

4.3.1 Proving the Algorithms

In order to prove the principal function of the tracking algorithms, the surveillance network and relevant air situations are modelled by means of computer programs and are implemented in a large-scale computer.

The following failures of radar post components have been analysed with respect to their effect on surveillance system operation:

- receiver failure (post transmits solely sensor track messages)
- radar sensor failure (relay function remaining)

- total failure (network splitting possible)

The simulation results are plotted graphically.

During the simulation runs, algorithms were improved and parameters were adjusted. At the end of the runs, it was shown that

- all tracks are initiated in spite of false target reports as well as expected,
- the amount of false tracks due to false target reports stay within the required limitations of less than 1 %,
- the track quality increases rapidly after initiation and remains high even at confusing target manoeuvers,
- track numbers are managed unambiguously,
- difficult air situations, such as crossing trajectories, formation flights, and temporary hidden terrain following flights are controlled successfully,
- operational constraints during build up, change or decomposition of the tracking network, such as net splitting and reformation, or the connection of additional compatible networks are practicable during system operation and do not cause any confusion or operational restrictions,
- the sensitivity of the surveillance system to failures of radar posts or of components of them is very small.

Figure 17 shows the tracking of two targets, flying crossing trajectories at equal altitude. The first intersection is rectangular, the second one is at an angle of 45 degrees. Track numbers do not change in spite of crossing. Due to the great number of simulated false radar echos, some false preliminary tracks appear but terminate after the first report, with one exception, which is reported twice (track number 2073).

Figure 18 shows an air situation with three formation flights of four targets. Each 15 radar posts are in operation. After a certain time at least three tracks are established for each formation. Since target discrimination by the radars differs from rotation to rotation, the updating of the separate tracks varies.

4.3.2 Realtime Test

The size of the tracking computer in each radar post is limited in its dimensions and its power consumption. Some of its properties are

- fixed and floating point arithmetic
- 16 bit word length
- internal memory 128 K Byte, with provision for expansion
- directly addressable 64 K Byte
- no auxiliary storage
- sufficient number of 16-bit registers
- operating speed of approximately 200,000 operations/sec.
- stored program: the operating system needs about 30 K byte, the user program up to 80 K byte and more, depending on the jammer tracking capabilities
- program language: high level language for algorithms, assembler for I/O-procedures.

For checking the realtime capability of the designed tracking algorithms performed by a relatively small process computer, three AEG 80-20 computers, similar to the expected tracking computer were interconnected (Fig. 19). The data links were not modelled but simulated in their most characteristic parameters. A central control computer imitated three radar sensors and supplied the three tracking computers with target reports corresponding to synthetic air situations. To get comparable results from the large-scale computer simulation and from the process computer simulation, identical air situation models were used. It was shown that this computer can handle about 100 targets, if the algorithms described above are employed. Simultaneous tracking of six jammers was simulated successfully.

4.3.3 Real Input Data Test

The input data for the demonstration of system function and for the real time test are derived from a synthetic air situation and modified according to the radars concerned. Both, the air situation and the radar characteristics are modelled by ESG with respect of particularities, specified by the German Air Force and by the manufacturers of the radars. To ensure that differences between the models and the real air situations or the real radar performances, respectively, do not effect the tests positively, real air situations were acquired by three radar posts and recorded simultaneously on tapes. The flight profiles for 21 jets and 5 helicopters are planned under the responsibility of ESG in accordance with the GAF and German Army pilots.

The recorded data of the three radars were filed chronologically and prepared for the replacement of the synthetical data. The same configuration of three interconnected tracking computers as for the realtime test was used to prove the effectiveness of the

tracking algorithms. The central control computer supplied the tracking computers with real radar data as if they were acquired in realtime.

The most important results of the simulation runs are:

- the real flight profiles were easier to track than the synthetical ones,
- because of the lack of radar resolution, tracking of formation flights is not as critical as expected,
- clutter is a severe problem; it has to be eliminated by filter algorithms - e.g. clutter mapper - before tracking,
- wrong manipulations of the operators at the radar posts, such as an insufficient false alarm suppression or an incorrect input of the local coordinates have to be taken into account when defining the algorithms and the operators manual.

5. SIMULATION OF THE FIRE CONTROL

The optimum coordination of fire between the weapon systems that can be employed is an essential system function. This task is performed at the lowest command level, i.e. both threat analyses and target allocation for the associated weapon systems - possibly of different types - take place at battery level (Fig. 20). The objective of fire coordination is to avoid overkills of individual airborne targets and to obtain an optimum fire distribution at a very low ammunition consumption in the case of several aircraft entering.

5.1 Approach

The sequence of the simulation activities provides for two worksteps, i.e. "simulation by large-scale computers" and "process computer simulation" with the following objectives:

- Simulation by large-scale computer
  - o functional proof of algorithms
  - o parameter definitions
  - o determination of the effectivity
  - o optimisation of procedures
- Process computer simulation
  - o realtime testing of functions/operational sequences
  - o determination of the procedure efficiency
  - o determination of radio link load
  - o determination of operator strain
  - o determination of computer workload

5.2 Models

Fig. 21 shows the overall model for the simulation of the fire control. Essential components thereof are as follows:

- Air situation model

  The air situation model covers both the actual air situation to be referenced for evaluation purposes, and the system air situation, acquired by the sensor network, which is received and evaluated both by the fire control vehicle and by the weapon systems.

- Fire control vehicle model

  The procedures covering threat analysis and target allocation were realized by the fire control vehicle. Essential parameters in the strategy of target allocation, among others, are as follows:

  - o behaviour of the incoming airborne targets
  - o performance of weapon systems
  - o status of weapon systems, e.g. availability, ammunition supply etc.

- Weapon system model

  The weapon system model includes the following:

  - o surveillance radar, including terrain shadowing
  - o action in the case of lock-on (probability to obtain a lock-on)
  - o weapon release (e.g. model on salvo sequence)
  - o determination of hit probability (inclusive impact on air situation)
  - o weapon system failure behaviour (status), inclusive ammunition supply.

Additionally, models for simulating data transmission (time behaviour, arising of interruptions), manual interventions, and for varying the deployment have been implemented.

5.3 Time Sequences

The situation in the timely sequence of threat analysis and target allocation is shown in Fig. 22. Incoming targets are entered in the intruder log as soon as they are within a minimum distance to the weapon system.

If they are determined to be a threat during further surveillance - as a result of analysing their course, speed and manoeuverability - they are entered in the allocation log. In the remaining time until allocation of the target to a weapon system, the optimum weapon system for fighting it has to be selected according to the strategy program. The time of target allocation must consider both the weapon effectivety range and the weapon system inherent reaction time including the projectile time-of-flight.

Figure 23 shows the data flow in the simulation system. While the procedures in the fire control vehicle are fully realized for simulation purposes, various sequences in the weapon systems have to be simulated by way of models. The latter case applies in particular to the functions of the search radar, lock on and determination of the hit performance.

5.4 Results

Figure 24 shows some results with regard to quality. The diagrams clearly show the increase in weapon system effectivity and the reduction of the ammunition to be used when a fire coordination is employed. The possible increase in effectivity obtainable by the system via early reconnaissance and proper weapon system operational guidance offers improvement factors of > 2.

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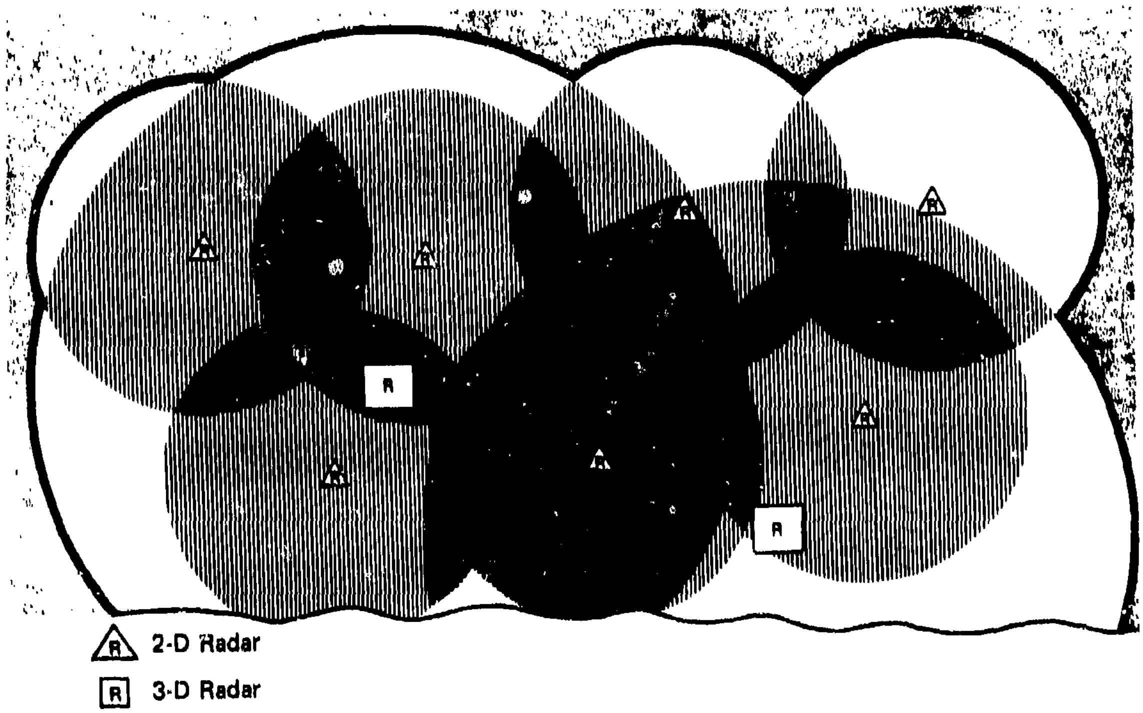


Fig. 1: System Surveillance Coverage

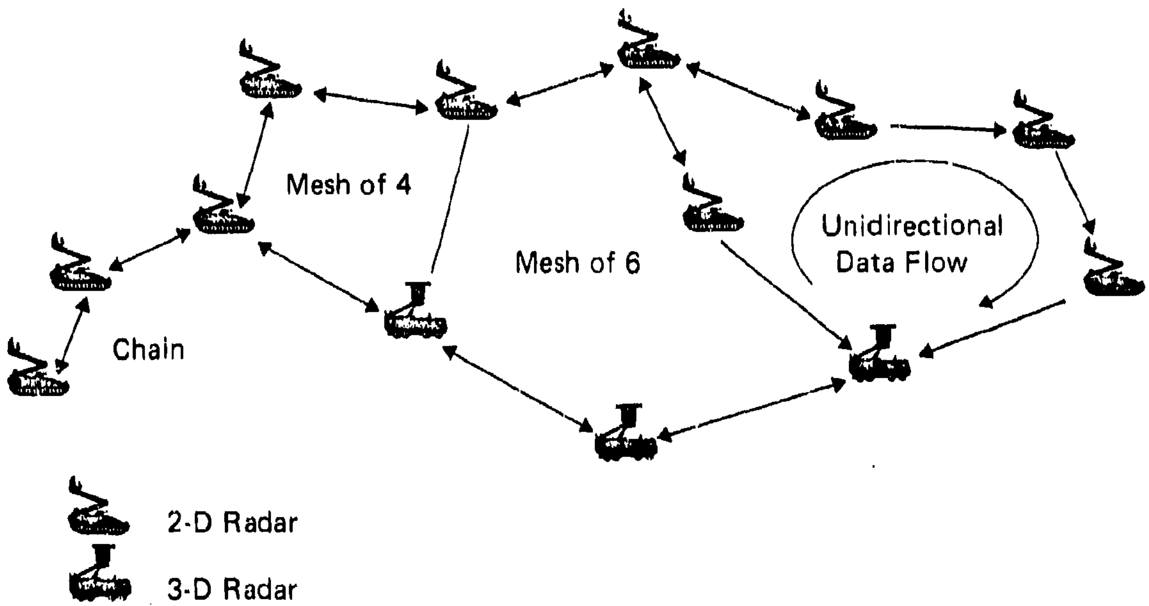


Fig. 2: Network Configuration

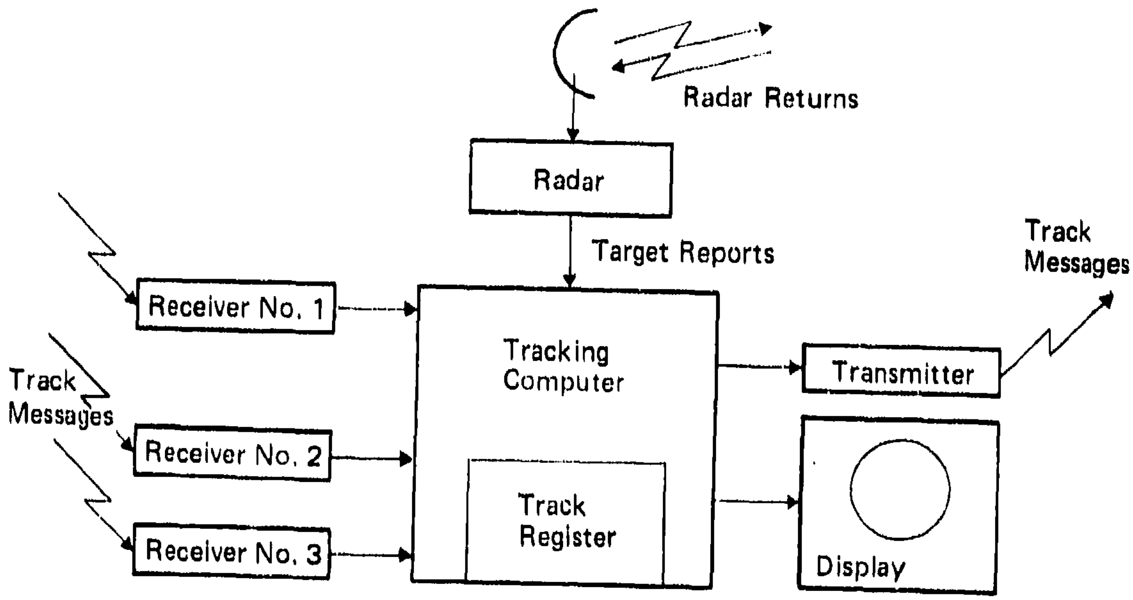


Fig.3: Radar Post Configuration

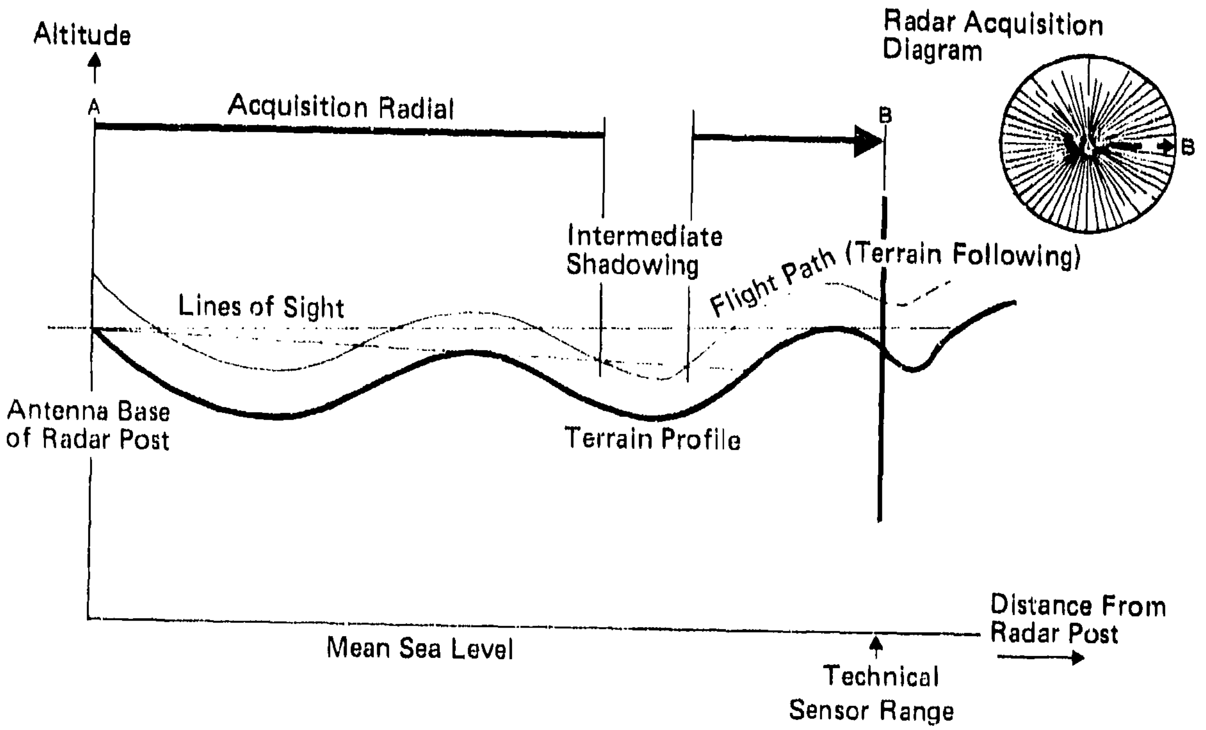


Fig.4: Generation of Radar Acquisition Diagrams

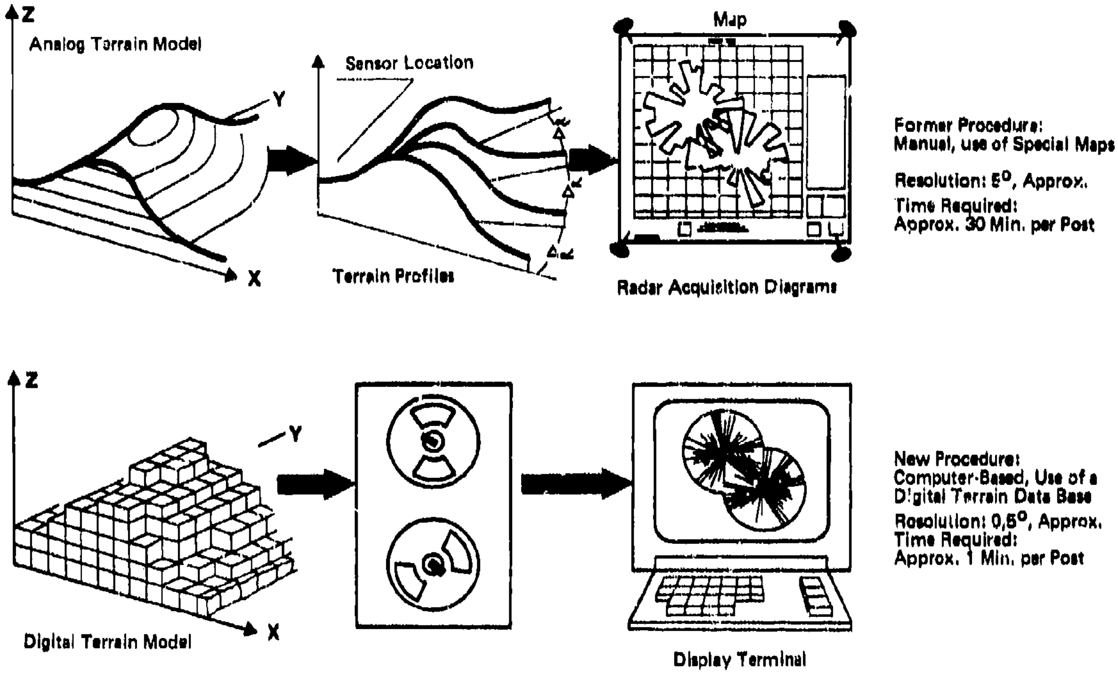
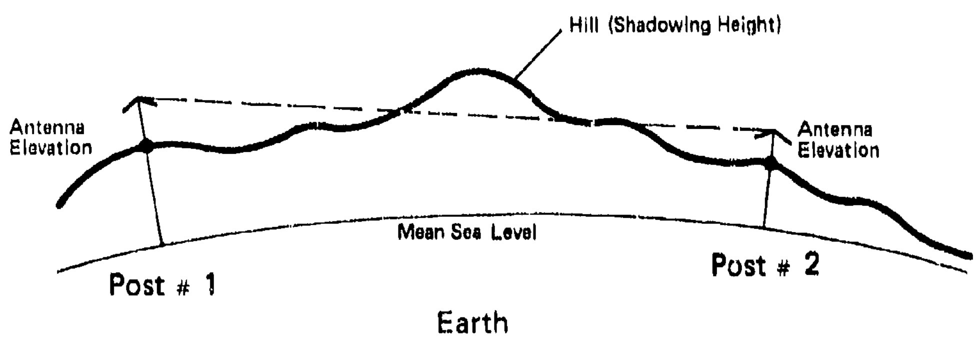


Fig.5: Planning of Sensor Location



Data link operation requires a signal-to-noise ratio

$$\boxed{a_{SN} \geq a_{SNmin}}$$

a_{SN} depends on the distance between the sensor and on the shadowing height

Classification:

$a_{SN} < a_{SNmin}$ → Radio Link, Not to Be Realized

$a_{SNmin} \leq a_{SN} \leq a_{SNmin} + XdB$ → Radio Link, Medium Quality

$a_{SN} > a_{SNmin} + XdB$ → Radio Link, Good Quality

Fig.6: Classification of a Radio Link

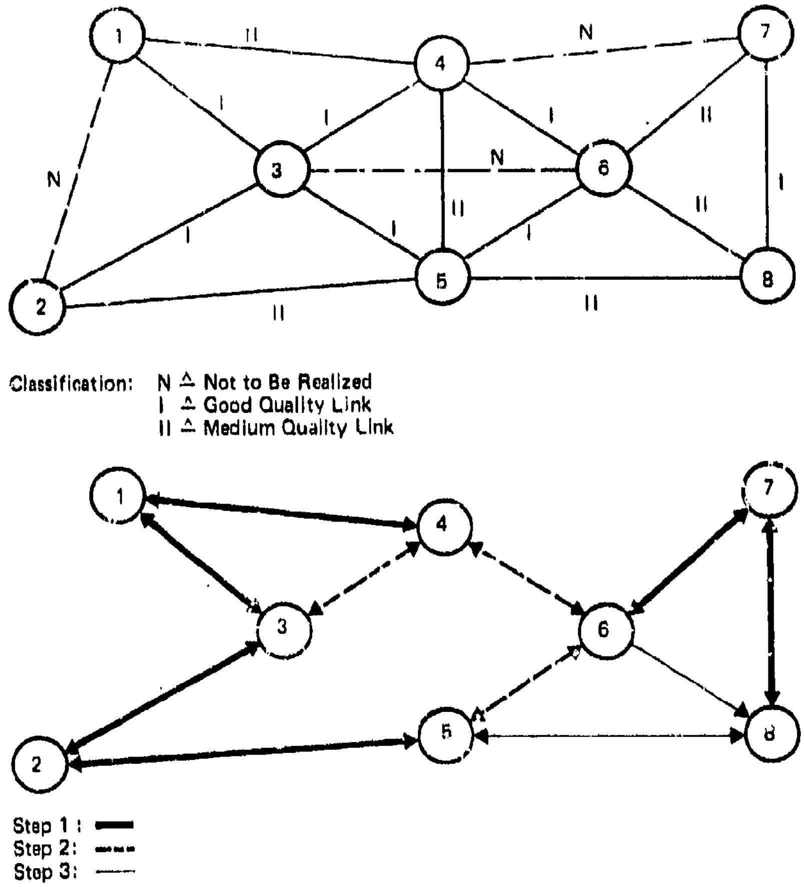


Fig.7: Planning of Network Structure

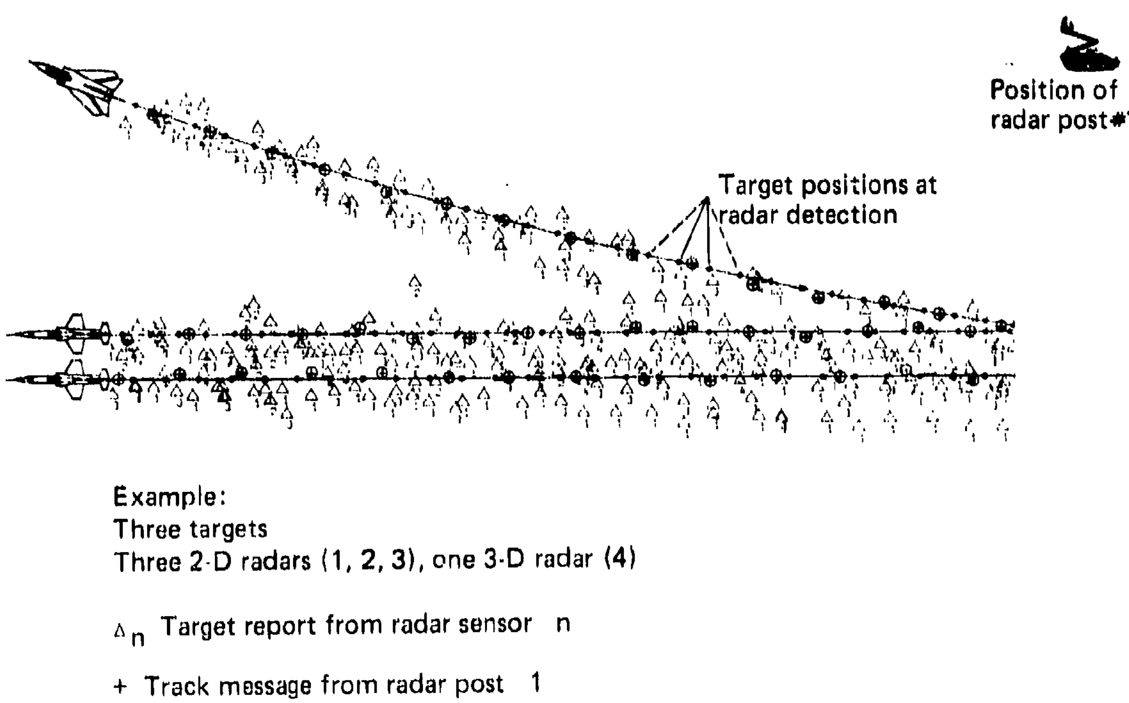


Fig.8: Multi Sensor Tracking

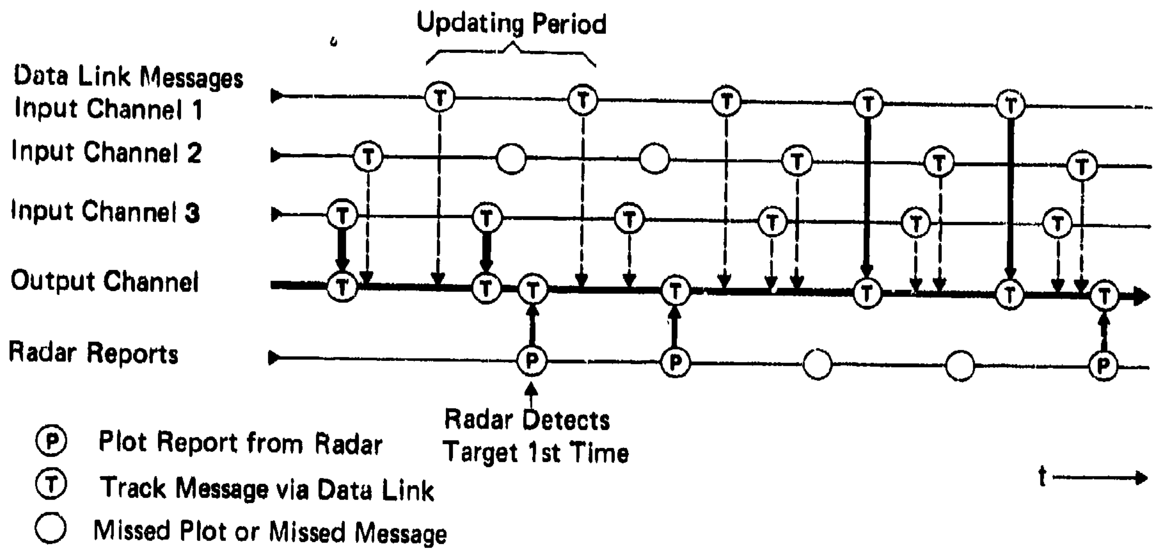


Fig.9: Track Message Reporting Procedure

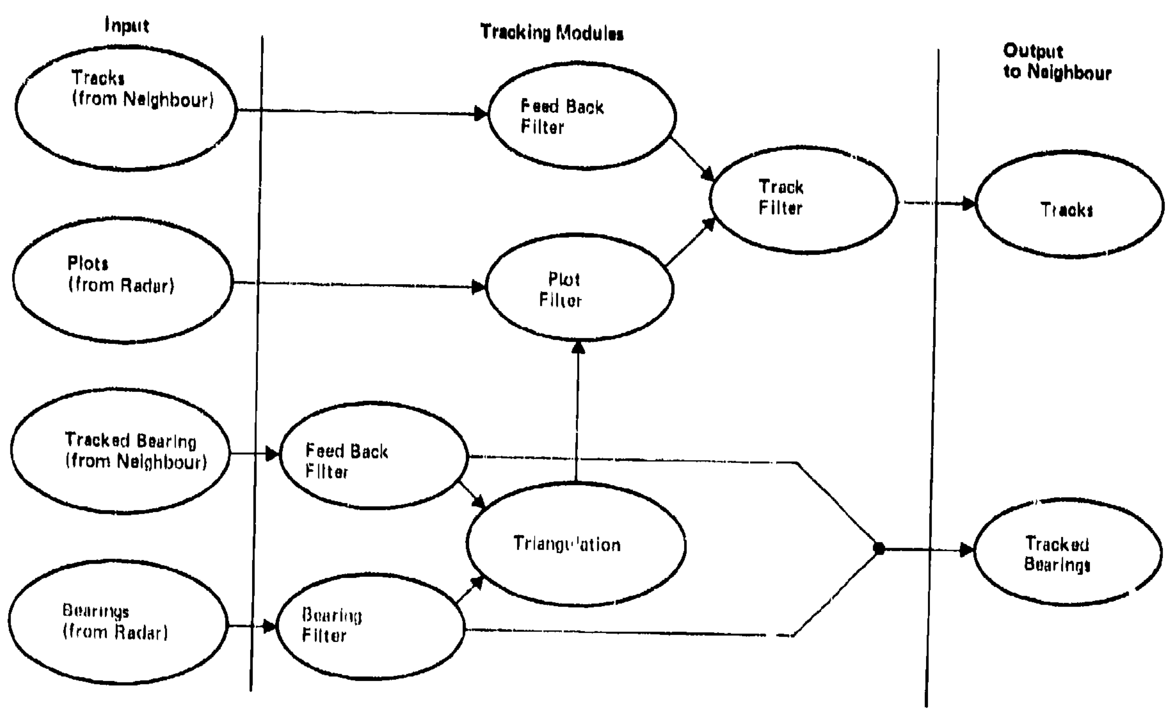


Fig.10: Data Processing

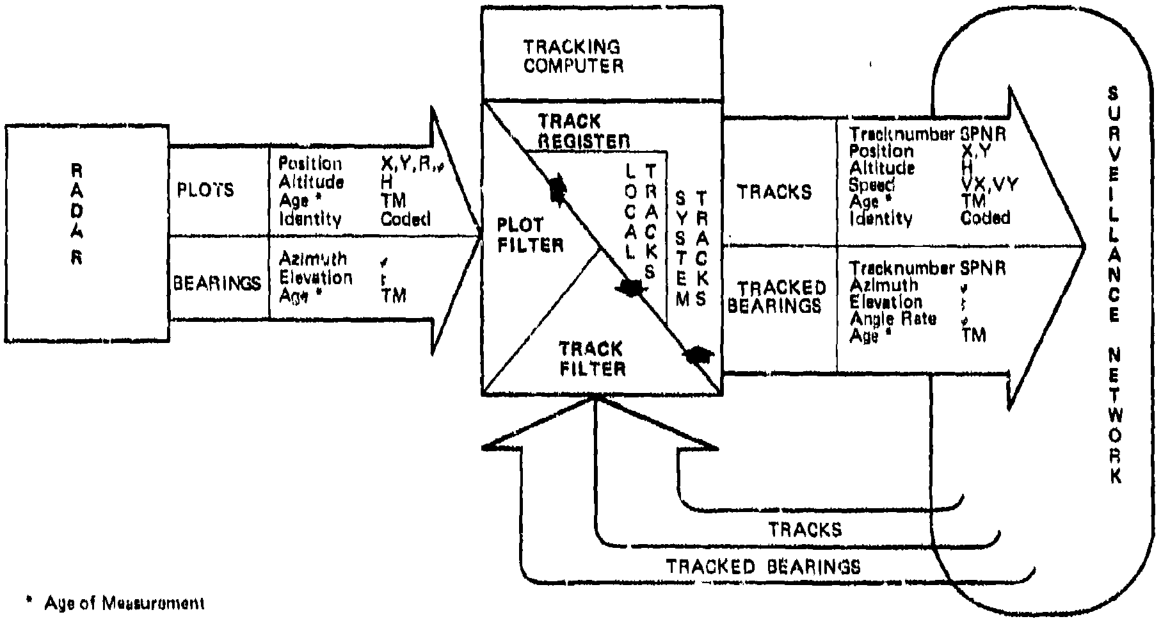


Fig.11: Track Data Flow

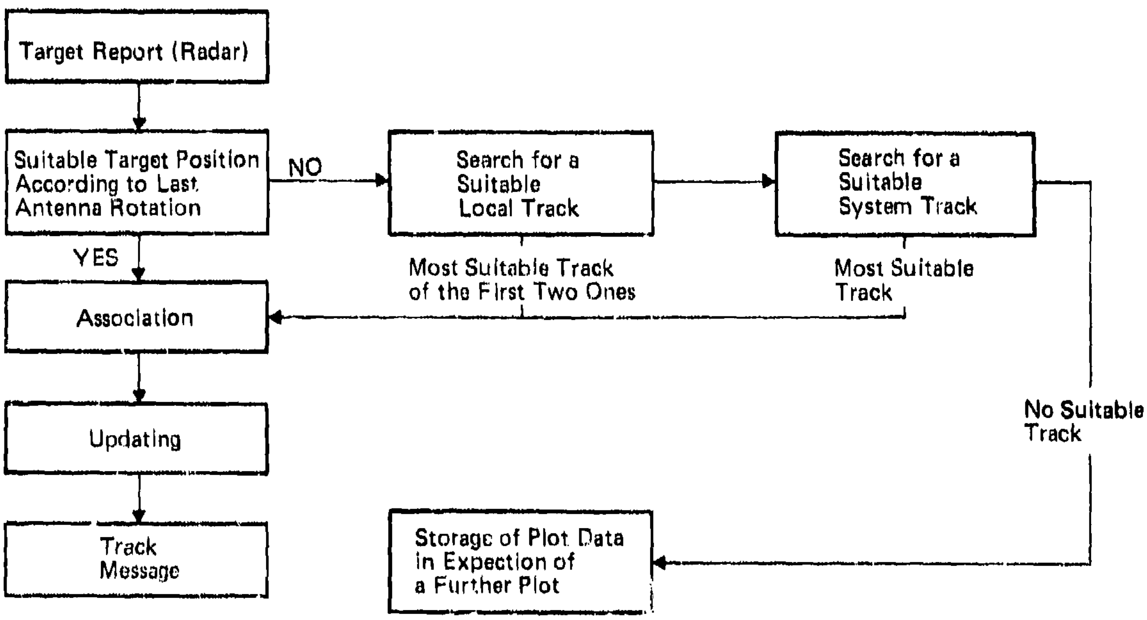


Fig.12: Plot Filter

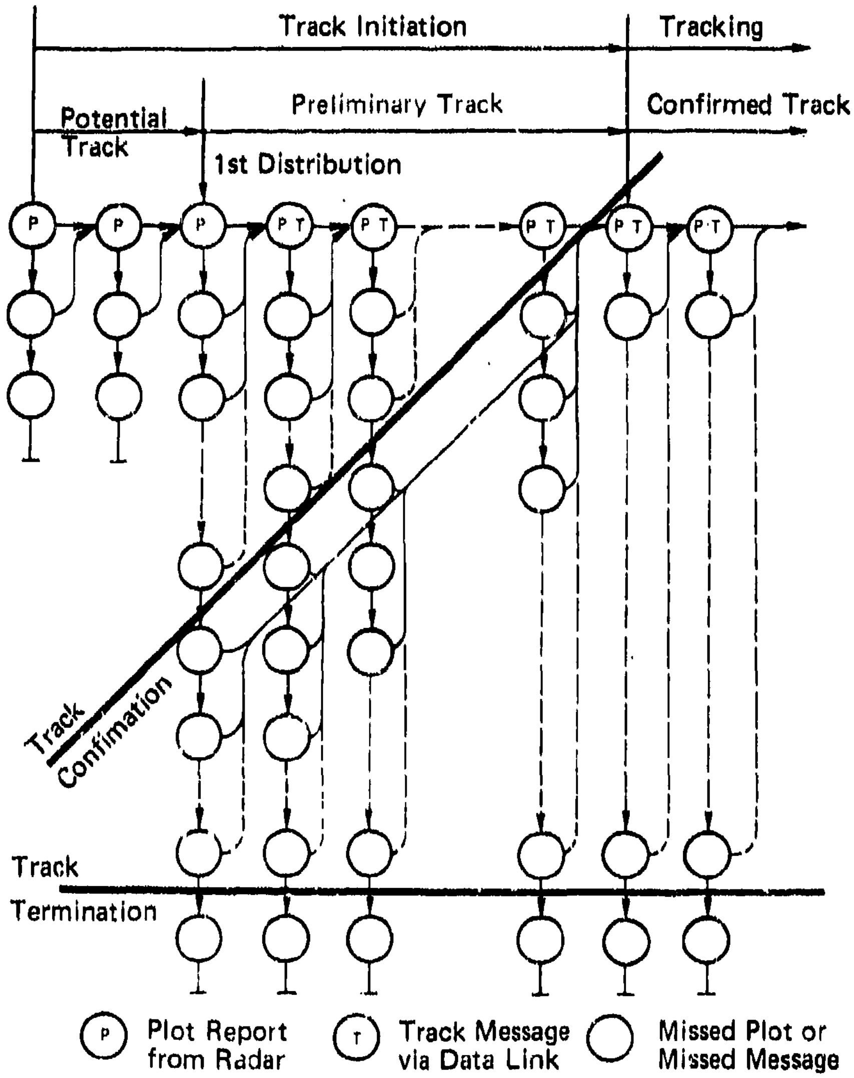


Fig.13: Track Steps

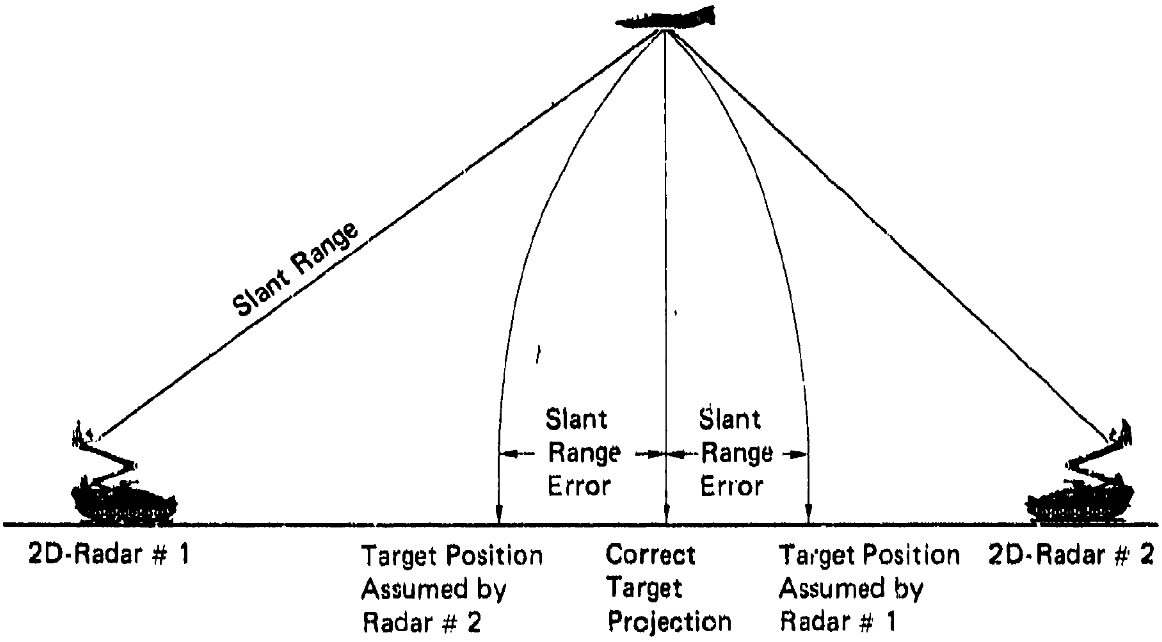


Fig.14: Slant Range Problem

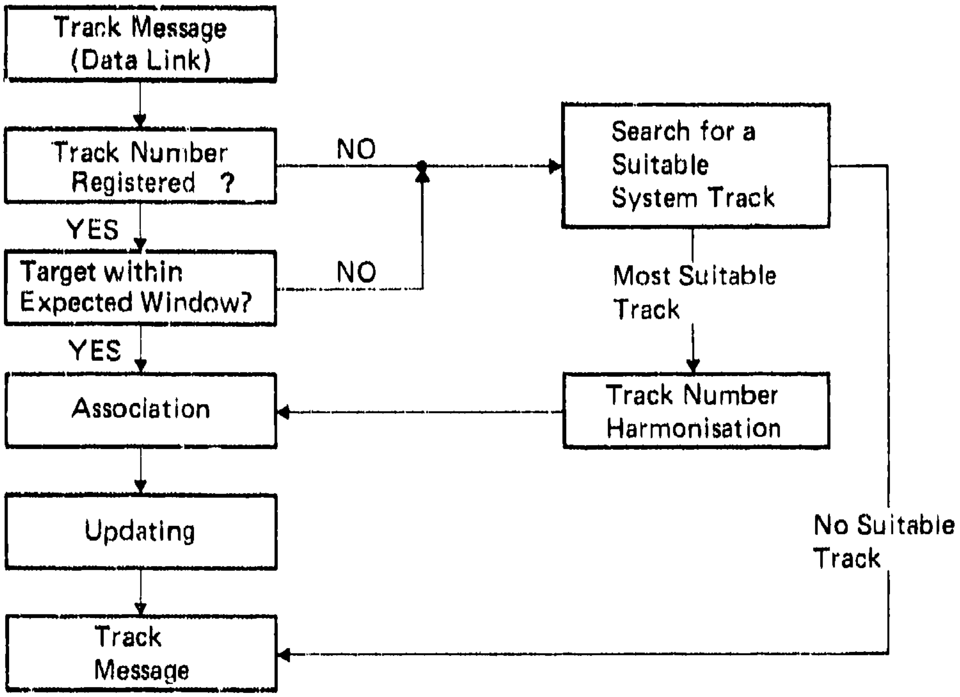
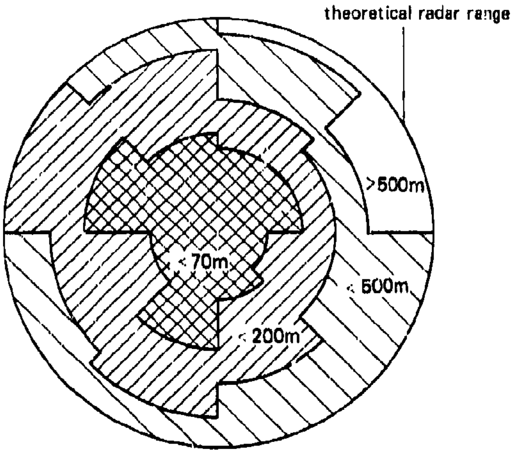


Fig.15: Track Filter



The indicated values show the relationship
between coverage and height layers

Fig. 16: Radar Coverage Model

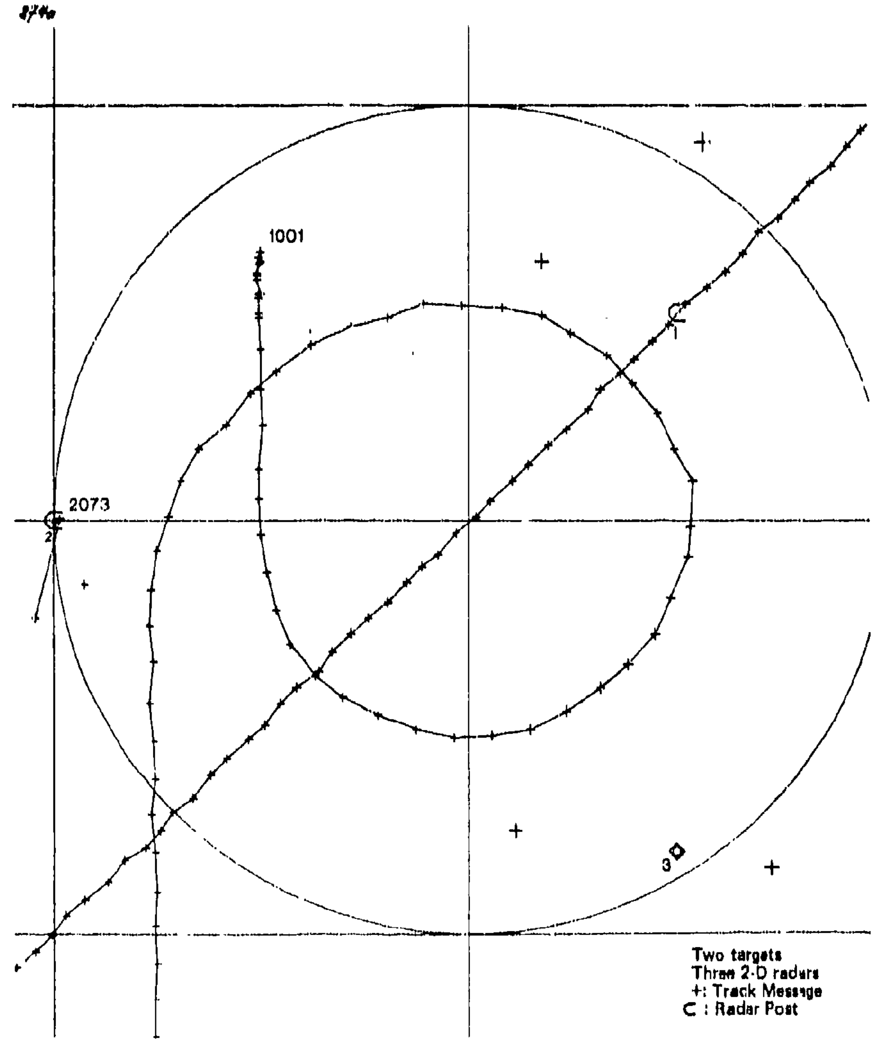


Fig. 17: Crossing Trajectories

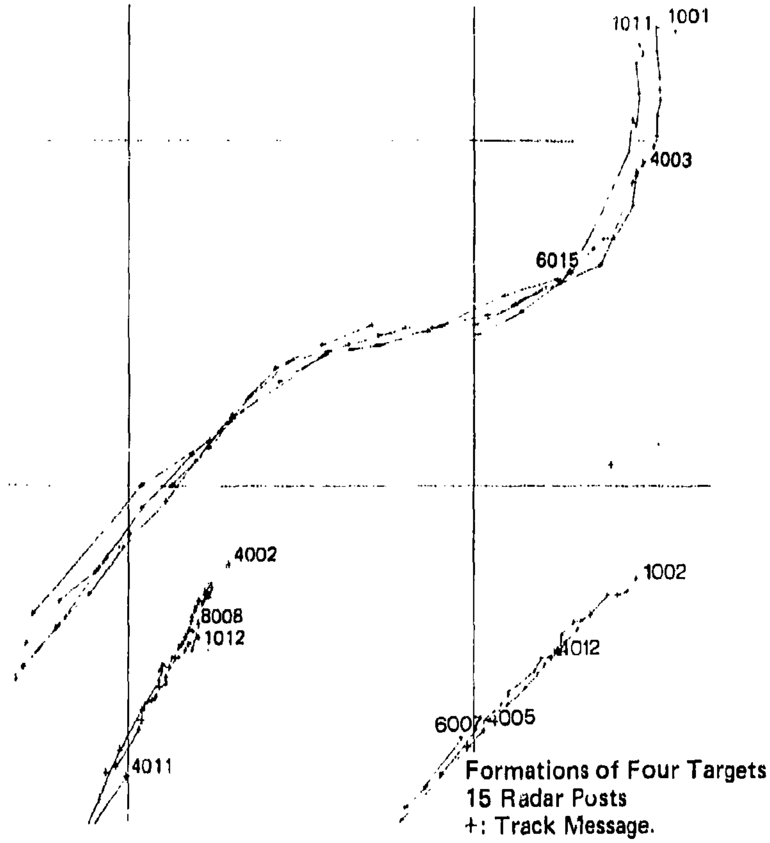


Fig.18: Formation Flight

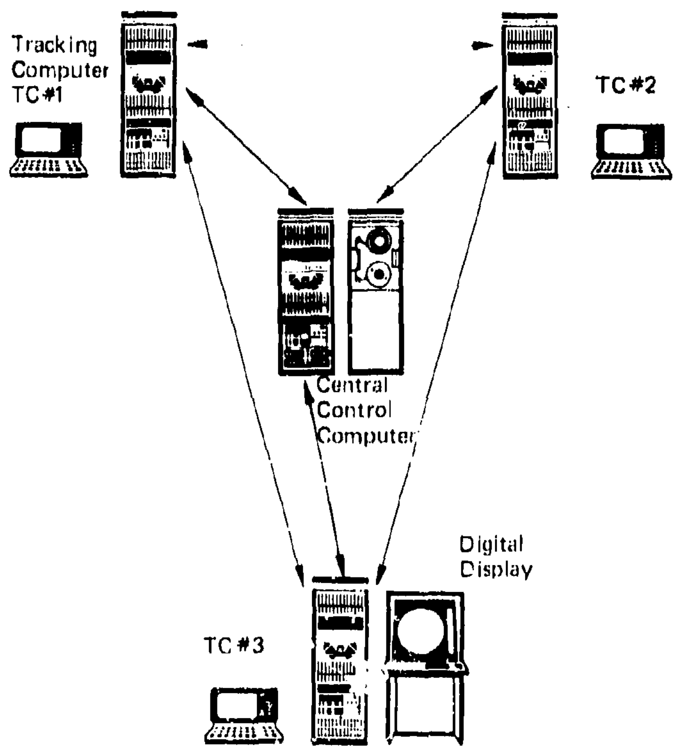


Fig.19: Realtime Test Configuration

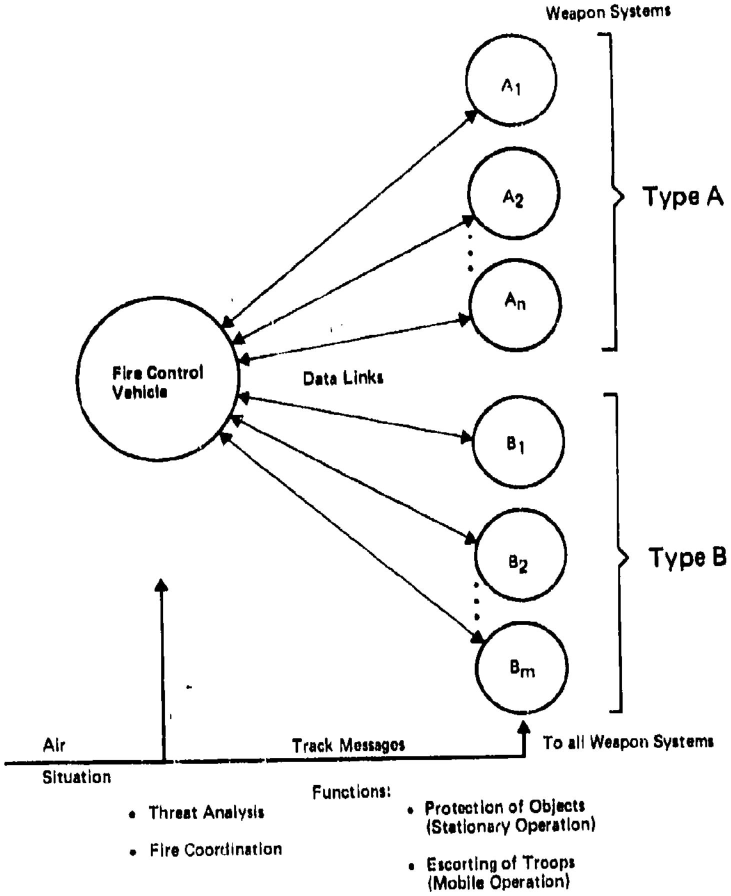


Fig.20: Fire Control Links

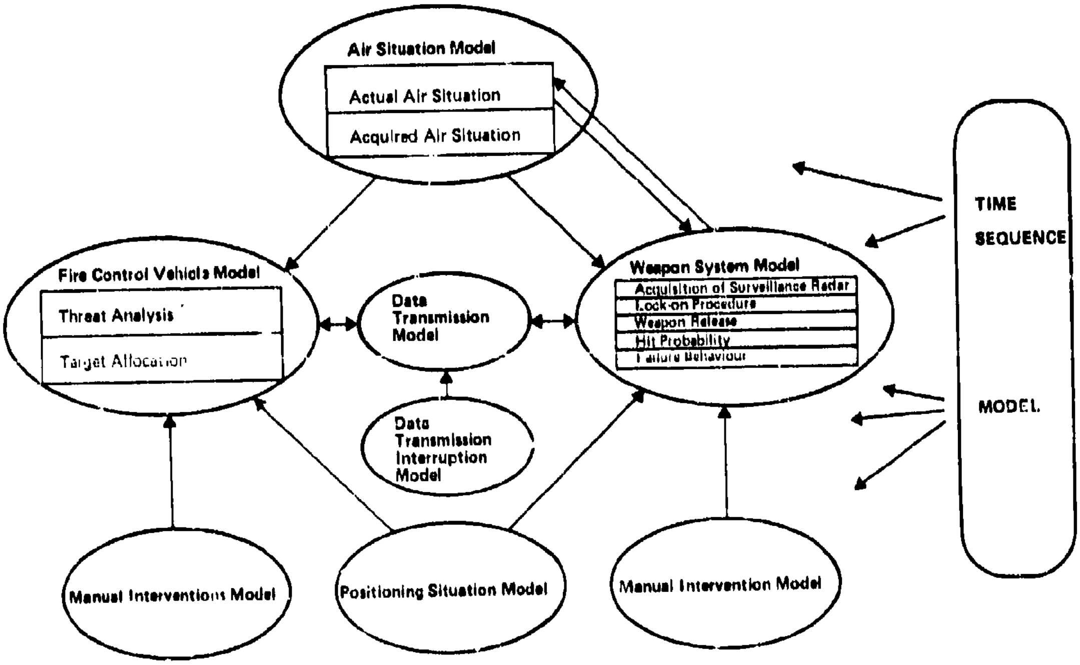


Fig.21: Model Interactions at Fire Control Simulation

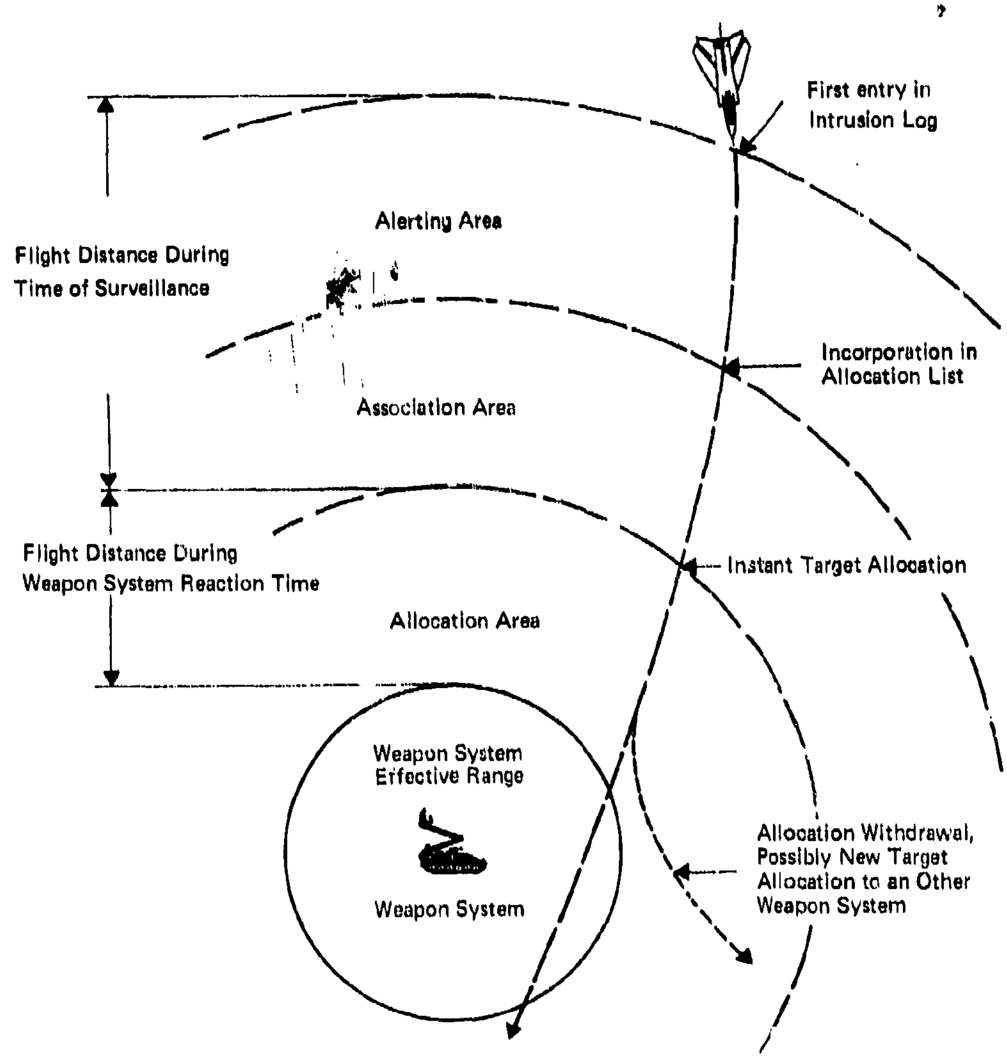
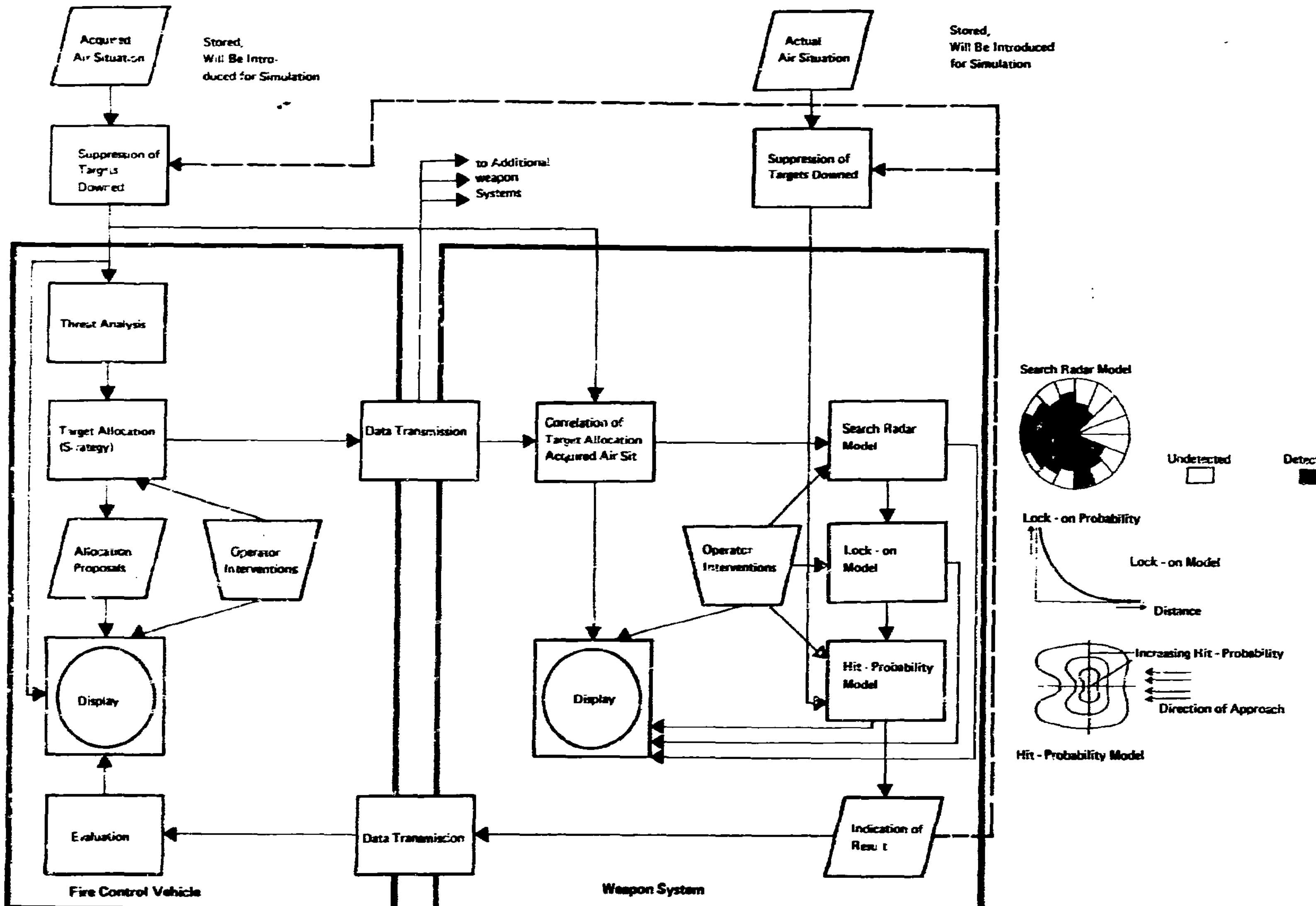


Fig.22: Target Allocation Time Sequence



FIFE CONTROL DATA FLOW

Fig.23: Fire Control Data Flow

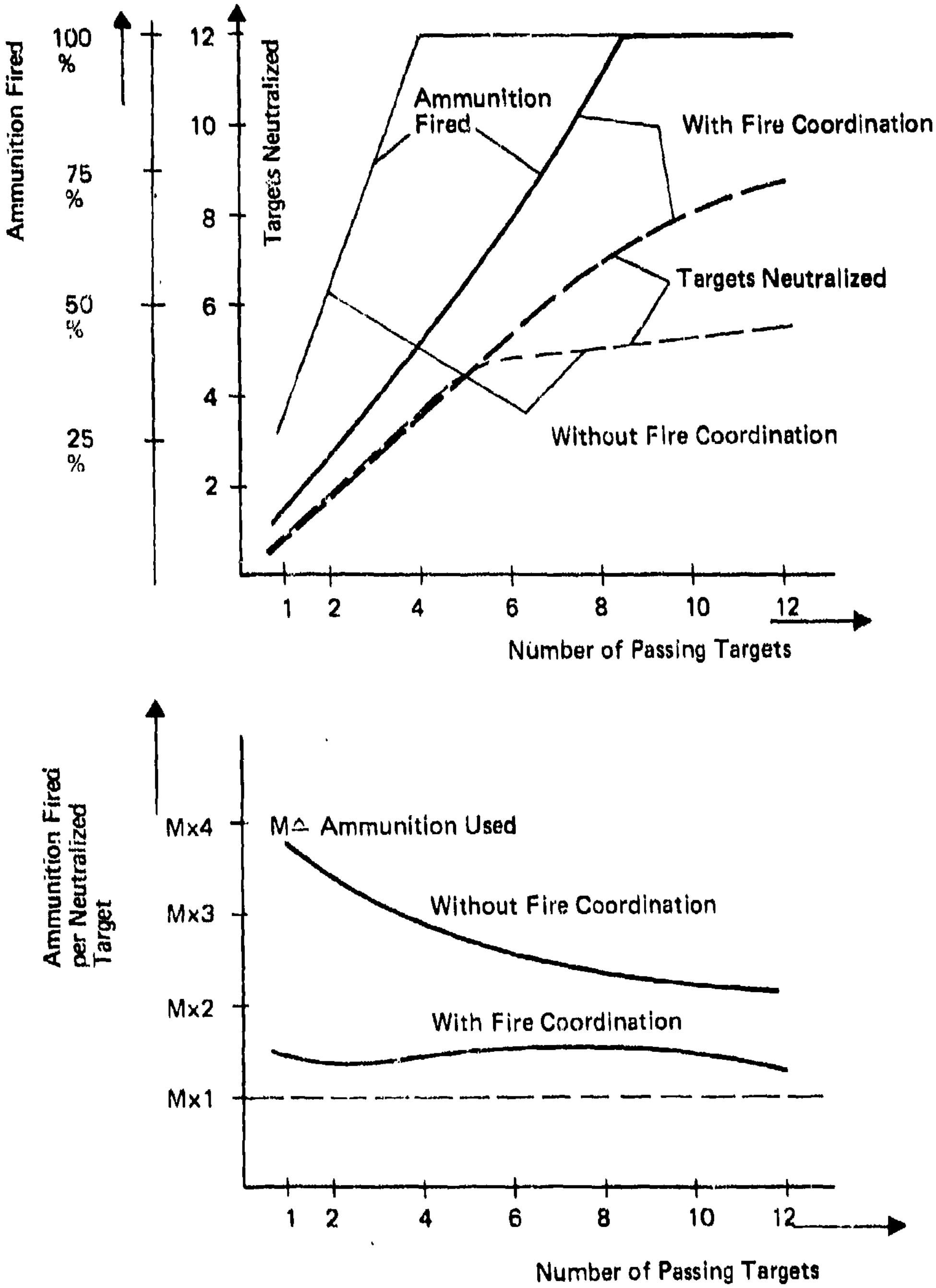


Fig.24: Increase of Weapon-System Effectivity

SIMBOX : A GENERAL PURPOSE DEFENSE SYSTEMS SIMULATOR

B Davy

Royal Signals and Radar Establishment
Great Malvern, Worcestershire, UK

SUMMARY

This paper describes a simulation tool of sufficient flexibility to meet most of the simulation requirements for a large variety of systems. Conceptually SIMBOX provides a box into which a user can insert objects typically found in a defense environment, such as aircraft, ships, sensors and weapons. These can be controlled by the user and the data generated as a result of interactions between objects (eg Plots, tracks, messages) can be extracted, in real time if required. This data can be logged for off-line analysis, analysed on-line, or passed to external processes or devices where interfacing to real or simulated system elements is required. The paper discusses the design principles of SIMBOX, outlines its capabilities, and gives some examples of its application.

1. INTRODUCTION

SIMBOX is a general purpose simulation system giving a user facilities for setting up and controlling a scenario of sensors, targets, weapons, communication systems and other objects typically found in a defense environment, and monitoring events as in a real system. Areas of application include

- i System element design and testing
- ii System integration
- iii Man/machine investigations
- iv Inter-system interoperability testing
- v Operator training
- vi Performance assessment
- vii War games

SIMBOX is not a simulator in the sense that it simulates any specific system or answers any specific question by itself. Rather it is a kit of parts which allows a user to build a simulator to suit his own requirements. To do this the user must supply an interface program containing user calls which tell SIMBOX what to create, what data to output, and how to control events.

The SIMBOX enivronment is built up from "objects" such as aircraft, ships, sensors and communications devices, which are created in a simulation box (normally of dimensions 1000 Km x 1000 km x 100 km), in response to user calls. These objects interact, producing data streams appropriate to the nature of the interaction and the state (as a function of time) of the objects and their surrounding environment. For example, a radar may interact with an aircraft, to produce a stream of data consisting of radar plot details, taking into account the state of the radar (power, beam shape etc), the state of the aircraft (echoing area, velocity etc) and other relevant details such as atmospheric attenuation, terrain screening and the effect of jammers. Similarly a communication receiver can generate a data stream consisting of a sequence of receiver messages, and so on.

The SIMBOX user can request output of these data streams, ie he can obtain a copy at the user interface of data pertaining to significant events occurring inside SIMBOX. Additionally, output can be directed to backing store for data-logging purposes.

Similarly, the user can make calls requesting output of data such as the current spatial co-ordinates of an object, or its real-time state. Other calls allow him to control SIMBOX operation, by steering or launching objects, or changing their parameters, and to schedule user procedures in which user calls can be placed, and output data processed.

At a higher level, the user can ask SIMBOX to integrate simulated sensor outputs into a common database, so simulating a data handling system. Further, these data handling systems can be drawn into a data communications net, with modelling of net protocols and operator actions. Activity at various interfaces of these high level structures can be monitored.

SIMBOX is specifically designed to allow simulation of complex systems in real-time. It is written in CORAL 66, and implemented on a DEC system 10 machine.

2. DESIGN PRINCIPLES

The fundamental principles around which SIMBOX is designed may be summarised as follows:

1. Fast run time
2. Ease of modification

3. Simple user interface

4. Appropriate accuracy

5. Processing options

Each of these will be considered in turn.

2.1 Fast Run Time

In many applications, where SIMBOX is interfaced to real hardware or man/machine interfaces, it will be essential for it to run in real time. Very fast processing is required if complex systems and large scenarios are to be modelled. A first requirement is of course an efficient high level language and for this CORAL 66 was chosen. Secondly, data structures must be carefully designed so as to minimise the overheads associated with accessing and updating data. SIMBOX uses packets exclusively for the building of data structures and for passing information to the user or between procedures. These packets are linked into chains, giving very fast access and largely eliminating the need for run time searching of data entries. The structures also allow dynamic storage allocation, with no problems associated with garbage collection.

Finally care must be taken to prevent unnecessary processing. An example of this in SIMBOX is the use of "lifetimes" in association with some complex calculations, where a calculation is inhibited if the result of a previous calculation of the same type is still valid in practical terms.

2.2 Ease of Modification

SIMBOX is designed to allow simple modification and enhancement, for example the introduction of new object types, to meet the requirements of future systems. This is largely engineered by a very extensive use of Macros, some 1000 of which are currently defined.

2.3 Simple User Interface

A user communicates with SIMBOX via a "user program" ie a set of procedures containing high level user calls. Facilities provided by the latter include

- i Object creation and deletion
- ii Steering control
- iii Real time parameter control
- iv Data I/o requests
- vi User program scheduling
- vii Data logging
- viii Trace and debug options
- ix Packet handling facilities
- x Utilities such as file handling and data print-out routines

Some of these facilities are further described below. In all cases the user calls are very flexible allowing a wide range of users to be catered for. These may range from those who are content to use SIMBOX on a black box basis, with perhaps scant knowledge of programming techniques, to those who wish to control every nuance of operation. It is possible to get hands-on experience very quickly and with little effort. This is very important if potential users are not to be frightened off by the inevitably long user guide. In all but the simplest of situations the output of a system simulation will rarely be what the user expected, and the tool will always be suspected. Thus analysis aids are provided, with data print-out facilities designed to build up the users confidence in the model. Also important is the need to protect the user from his own errors. Extensive error detection and reporting mechanisms are provided, together with trace and debug facilities.

2.4 Appropriate Accuracy

It is considered adequate that the accuracy of the data produced by SIMBOX is typical of that which would be produced by a real system. For example the quantum of range measurement is 1 metre. This allows the use of integer data represention with a consequential increase in processing speed.

2.5 Processing Options

Various options are available to allow tailoring of SIMBOX processing and the depth of simulation to suit the task in hand. If for example SIMBOX is being used to assess the performance of a radar, say in terms of probability of detection of a target as a function of target range, then sophisticated simulation of the radar may be requested. On the other hand, if plots are being generated for output to a display to test operator functions then a very simple radar model may suffice, and SIMBOX can be instructed to avoid unnecessary processing.

3. OBJECT CREATION

An object in SIMBOX is described primarily by an object code, containing various fields such as type (aircraft, ship, radar etc), subtype (submarine, tanker etc. for ships), role, national identity and so forth. An object is further described by a set of real time parameters. In the case of a radar for example these will include the current prf, aerial pointing angle and so on. Real time parameter values may vary with time as a SIMBOX run progresses, either in response to user requests or as a result of SIMBOX internal activities.

SIMBOX contains a library of objects incorporating object codes and real time parameters and a user can describe an object in a creation request simply by supplying the library name. At the other extreme the user can specify an object completely by supplying a full set of object code field and real time parameter values. In between these extremes various mixes of user supplied and library supplied values can be requested. New object descriptions can be added to the library, and henceforth called by use of a library name.

Groups of objects are generally linked in trees which denote a "carrying", "carried by" relationship. An example of a tree structure is shown in Fig 1. In fact the tree is the basic unit of construction for a user; a single object is a tree containing one object only. A tree can be of any complexity and there is no logical limit to the number of trees which can be created. When SIMBOX is asked to create a tree it must be presented with information describing the objects in the tree (most simply the library names) and the tree structure. Inside SIMBOX the tree structure is morrored by cross links established between the data structures describing the individual objects. Datasets describing object trees are held in disc-based files called "scenario files". In effect these are tree libraries, and a user can call for the creation of one or more trees simply by giving SIMBOX a record number and/or filename. Facilities are provided for interactive inspection and modification of the libraries.

4. STEERING

Object trees are steered through the simulation space according to instructions held in "steering packets" which may be generated at any time and attached to a chain held by the tree. Conceptually there are two types of steering packet. In the first, the packet describes a simple manoeuvre and the duration of the manoeuvre, either directly or by specifying a terminating condition. For example, the description might mean "continue existing climb rate and execute a 1g turn clockwise until heading is greater than 70 degrees". On completion of the manoeuvre the next packet on the steering chain will be picked up and obeyed if there is one; otherwise the object will maintain constant velocity until such time as a further steering packet is supplied. In the second type the packet describes a continuous pattern, such as a racetrack or a sequence of random turns, which the steered object will follow until a new steering packet is supplied.

A wide range of options is available to the user as to how he exercises steering control. He can fill out and plant steering packets himself at one extreme, or at the other he can enter interactive dialogue to request SIMBOX to handle the details for him. Steering information can also be incorporated in scenario file descriptions.

5. OBJECT CO-LINKING

As new objects are created, SIMBOX automatically generates links between the new data structures and those corresponding to previously created objects as required. In particular, "interest chains" are established for each object, to define a limited environment of interest to that object. For example, ships, aircraft, and jammers on the appropriate frequency band will be of interest to a radar, while sonars will not be of interest. In fact there are two types of chain, interest chains which define the environment of current interest (eg for a radar, targets having a significant probability of detection and in line of sight) and possible interest chains which define other objects which may in time become of current interest. These chains form the basis of scheduling activity inside SIMBOX and are a powerful mechanism in preventing unnecessary processing. Co-linking and the associated scheduling of processing activity takes place only as required. If for example a tree is created consisting of a ship carrying an aircraft which in turn carries a radar, then co-linking of the radar environment and calls for the radar simulator will not normally be made until the aircraft is launched from the ship. User options are available to allow control over the co-linking mechanism if required.

6. OBJECT NAMES

SIMBOX generates a unique name for each object which it creates. This is returned to the user either directly or via various search routines which are available to the user. The name is used subsequently in user calls which request some operation on an object, say a request for output, or the planting of steering information. Also, a user can attach his own names to objects. He may wish for example to attach a common name to all members of a group of objects, say all objects launched at various times from a common carrier. Or he may wish to tag an object inside SIMBOX with the identification of an external element, say an external track number, or the code number of the operator responsible for steering the object. A user name may be supplied in two ways. In the first the name is associated directly with a specified object. In the second the name is applied to the view of one object as seen by another object; eg for a radar/target pair, the name will be associated with the radar plot or track list entry associated with the target, rather than the target itself.

7. DATA OUTPUT

Output of information from SIMBOX can be organised in various ways, including:

(a) Single shot output of data such as time or object spatial co-ordinates.

(b) Repetitive output at user selected intervals of data such as object co-ordinates or real time parameter values.

(c) Output at the time of significant events, such as the output of a radar track list entry whenever the entry is updated.

Data can be output directly to the user program, directly to peripheral devices, or both. If output to the user program, the data is packed into packets which are linked onto user data chains, in time order. Separate chains are maintained for each object for which output has been requested, with access via the object name. If output is to peripherals, the data is annotated according to a user specified verbosity, and written directly to a user specified file.

In all cases, output is controlled by a simple user call specifying the nature and format of the output required. There is no logical limit to the number of parallel output data streams which can be obtained from the various object interfaces.

A user may also wish to organise output from his own user program. A set of high level calls are provided for this purpose to relieve the user of the need to know the details of I/O channel utilisation.

8. COMMUNICATION NETS

SIMBOX currently can model a Link 11 data net. Other data nets are to be incorporated.

If an object has object type aircraft, ship, airfield, port, land vehicle, land weapon site or land op centre it can become a Link 11 PU, providing that it carries a Link 11 receiver and transmitter. A user call LINK 11 INITIALISE is used to draw objects into a net. This names the objects which are to become PUs, allocates track number blocks, PU numbers and command responsibilities, defines net operating details such as baud rate, and specifies the polling sequence.

A PU thus formed is allocated an "integrated data base", into which data received from its own Link 11 receiver and data received from its own sensors are integrated. Actual message transmission starts after the user has made a second call, LINK 11 START. The PU nominated as net controller then polls the net in accordance with the previously given polling sequence. Polled PUs transmit message streams appropriate to the contents of their integrated data bases. Message content, transmission frequencies, allocation of reporting responsibility etc follow the Link 11 rules as defined in the STANAG and SOPs.

Message transmission is simulated in terms of time delays and garbling due to propagation effects or jamming. Whether or not any message (including control messages such as picket stop) transmitted by a PU actually arrives at the receiver of another PU depends on the state of affairs at the time of message transmission, taking into account the transmission range, the current transmitter power, the jamming situation etc.

As part of the description of the Link 11 receivers and transmitters (real time parameters) provided at the time these objects are created the user supplies (or calls from the library) a description of the Link 11 implementation in terms of the recognised message catalogue, the implemented fields of each message and the interpretation to be placed on field values. He can also supply details of filters for application to the receiver and transmitter message streams. These details can be different for each PU.

The user can obtain copies of messages appearing at various points in the system, using the output facilities mentioned previously. Calls are also available to allow inspection or modification of the integrated data bases.

A user may wish to interface to an external data handling system, or to a simulation of such a system held in his own program. In this case he can create a PU inside SIMBOX but inhibit the internal data base integration for that PU. User calls are available which then allow him to interface to the external system, while SIMBOX still simulates the rest of the net.

9. THE USER PROGRAM - AN EXAMPLE

An example of a typical user program is given in the appendix. The example chosen is one of radar tracking assessment, the program printing out the probability of tracking a target by an airborne system as a function of target range. The procedure USER SETUP is called by SIMBOX at clock time zero to allow the user to set up the initial scenario and I/O requests, and to schedule any other user procedures. In this example a user procedure is scheduled to be called at intervals corresponding to the rotation period of the radar aerial to allow a count of the number of radar track list entries updated in the preceeding scan.

The example is given primarily to illustrate the typically small size of a user program in relation to the overall simulation task. In deriving the output data SIMBOX will take into account factors such as aerial beamshape and other parameters of the radar, the engagement geometry, the effect of a curved earth, atmospheric attenuation and diffraction, target echoing area fluctuation, and the parameters of the tracking algorithm.

10. APPLICATIONS

Figs 2 to 4 illustrate various applications of SIMBOX.

In Fig 2, a radar performance is being assessed. The user program makes user calls requesting scenario creation and radar track output, which is analysed in the user program. This class of application is exemplified by the program shown in the appendix. The range of applications like this is virtually unlimited; examples are data link loading studies, investigation of track correlation problems, the affects of jamming and s… on.

Fig 3 shows SIMBOX interfaced to a real system element; in this example a tracking algorithm software package is being tested. The user program sets up a radar and target scenario and requests plot output from the radar and navigation output from the targets. The latter (actual target position) can be compared with the tracker derived position to assess tracker performance.

Fig 4 shows SIMBOX interfaced to a data handling system. SIMBOX simulates the entire environment which would be seen looking out from the data handling system interface: ie own sensors and carrier, other net participants with their sensors targets, jammers etc. Data from the simulated own sensors (including received communication messages) is passed from SIMBOX to the data handling system. In the reverse direction go communication messages from the DHS and sensor controls resulting from operator actions.

SIMBOX can be similarly connected to a number of real systems to provide a test bed for studying interoperability problems.

11. CONCLUSION

SIMBOX has proved an effective tool in support of a major system development project. It has been used extensively for display simulation, radar assessment and the study of various aspects of tracking, correlation and data link operation.

In a typical user application SIMBOX may load up to 100K of program (36 bit words) together with 150K of data. Obviously there are problems in gaining user acceptance of a program as large and complex as this, and in fact a substantial proportion of the software is devoted to the task of easing these problems by supplying comprehensive analysis and diagnostic aids. In practice, user acceptance has been good.

It is difficult to give performance figures without being specific about the nature of the scenario and the application. As a guide however in an application such as that shown in Fig 4 a peak scenario of 800 targets can be handled in real time, with a typical mix of aircraft carrying jammers, aircraft carrying IFF equipment, and so on. This figure relates to a KI10 processor, At least twice the performance can be expected from the more modern KL10 processor.

It is envisaged that SIMBOX will form the basis of many test rigs and training simulators in a variety of systems; the advantages to be gained in terms of compatibility, standardisation and resource sharing are obvious.

APPENDIX.EXAMPLE USER PROGRAM.

```
'CORAL'
'PROGRAM'SIMBOX;
'LIBRARY'("SYS:USECOM.CRL");
'SEGMENT'EX6;
'BEGIN'


'INTEGER'RADAR NAME,NAME,AC NAME;


'PROCEDURE'USER SETUP,
(========================)
'BEGIN'
        'COMMENT'CREATE AEW SYSTEM (TREE NO 4 OF AEWS SCENARIO FILE.
        THIS WAS STANDARD PATROL RACETRACK PATTERN);
        AC NAME:=INPUT TREE("AEWS.LIB",4,OFF);(DIALOGUE SWITCHED OFF)
        'COMMENT'SEARCH FOR THE NAME OF THE RADAR IN THIS NEW TREE
        AND REQUEST OUTPUT FROM IT (I/O CODE 8=TRACK UPDATE DATA);
        FOR TREE OBJECTS(AC NAME,AIRCRAFT,RADAR,AEW,NAME)'DO'
        'BEGIN'
                RADAR NAME:=NAME;
                REQUEST OUTPUT(RADAR NAME,RADAR,RTIO,8,0,ON)
        'END';

        'COMMENT'INPUT SCENARIO FILE CONTAINING 100 TARGETS.DIALOGUE
        SWITCHED ON TO ALLOW INTERACTIVE SETTING OF VELOCITY,HEADING ETC;
        INPUT SCENARIO("RAID.LIB",ON);
        'COMMENT'AEW RADAR WILL HAVE 10 SECS AERIAL ROTATION PERIOD.
        ARRANGE FOR USER PROC 1 TO PICK UP THE REQUESTED RADAR OUTPUT
        ONCE PER SCAN;
        SCHEDULE(1,10000,10000);
'END';

'PROCEDURE'USER PROC1;
(==========================)
'BEGIN'
        'COMMENT'COLLECT REQUESTED OUTPUT DATA FROM RADAR'S USER DATA CHAIN.
        COUNT OF NUMBER OF PACKETS WILL GIVE NUMBER OF TRACKS IN TRACK LIST;
        'INTEGER'N,P;
        N:=0;

        'FOR'P:=TAKE IO PACKET(RADAR NAME,0)'WHILE 'P'NE'0'DO'
        'BEGIN'
                N:=N+1;
                RELEASE PACKET(P)
        'END';
        NL;
        TYPE("REV NUMBER "); TYPEOUT(CLOCKTIME/10000);
        TYPE("  NO OF TRGTS IN TRK LIST=");TYPEOUT(N);
'END';


'END'
'FINISH'
```

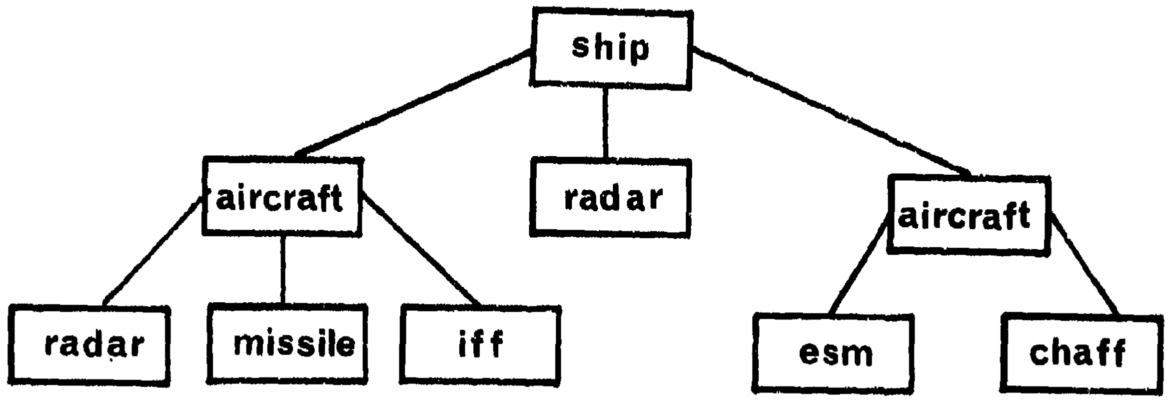


Fig.1 Object tree

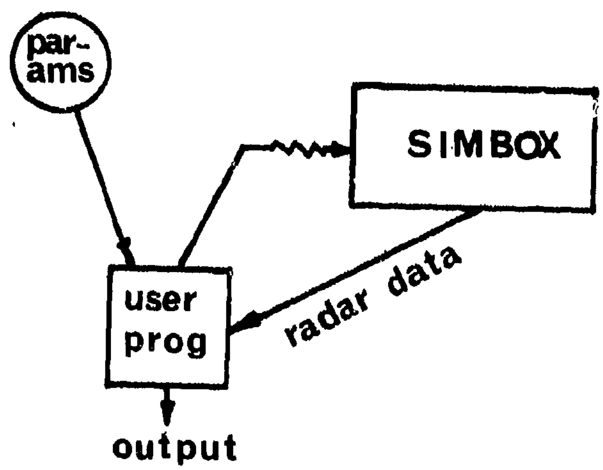


Fig.2 Radar assessment

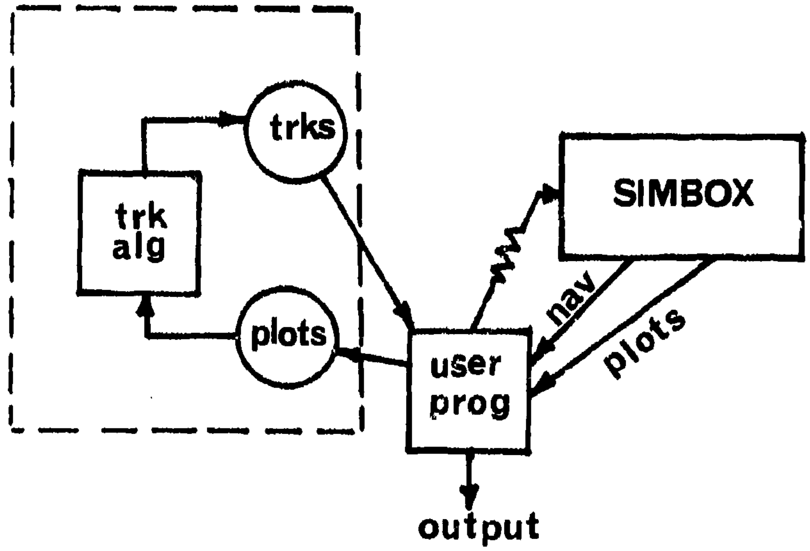


Fig.3 Tracker test

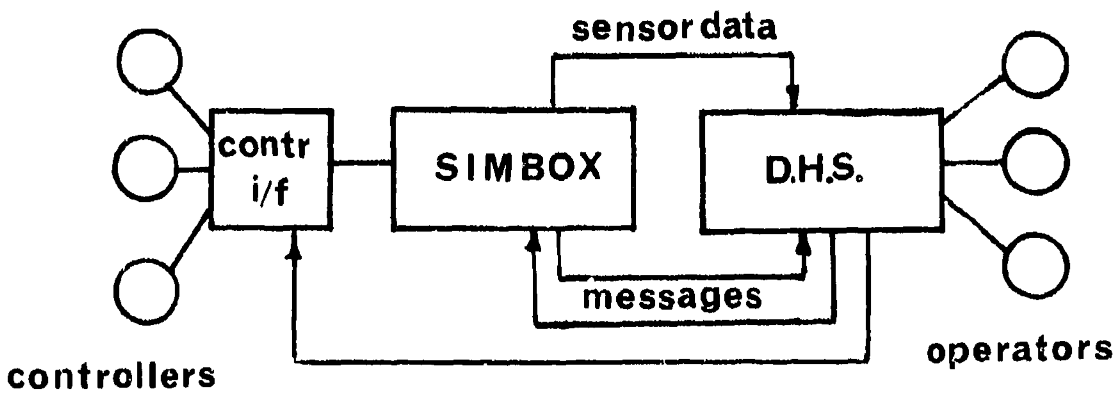


Fig.4 D.H.S. test rig

THE APPLICATION OF MODELING AND SIMULATION TO THE DEVELOPMENT OF THE E-3A

A.R. Shanahan
The MITRE Corporation
Bedford, Massachusetts 01730

SUMMARY

The E-3A Airborne Warning and Control System (AWACS) is a newly developed and sophisticated airborne radar, communications, and command-and-control system. It has been designed to perform a function never before possible: all-altitude surveillance of large volumes of airspace in the presence of severe ground clutter which results from operation over land. The development of this advanced technology system has been difficult but successful. Modeling and simulation have played an important role in this success.

Modeling and simulation served a variety of functions throughout E-3A development. They assisted in designing key subsystems such as the radar, integrating the overall system, developing the operational computer software, predicting system performance, projecting mission effectiveness, and advocating the system and its capabilities. Rather than describe any one of the many E-3A simulation models in depth, this paper focuses on the modeling diversity required to satisfy various E-3A program needs during different stages of system development. Thumbnail sketches of several representative models are included. This case history reveals that models and simulations were necessary and important tools in the development of the E-3A. Their contributions were both substantial and widespread. Several valuable lessons were learned in the process.

1. INTRODUCTION

1.1 Overview

Modeling and simulation have been applied liberally throughout the E-3A program. Even before there was an E-3A program, they were used extensively to establish the system's theoretical feasibility and to bound its performance requirements. In the early days of system development, simulation aided in the actual subsystem design, most notably of the radar subsystem. Later it was applied to the problem of determining the appropriateness of various hardware and software designs over a range of operational situations. The design of an effective target tracker was one of the more noteworthy development hurdles during this period. Accurate radar performance prediction then became the critical concern, and a family of models were developed to perform this function. These models were developed in an iterative fashion as system flight test data became available over time.

Modeling and simulation were extremely valuable in the early- to mid-seventies for addressing the system-advocacy issues of the times, issues that could not be addressed by flight test until years later. In one instance an "obvious fact" was shown by simulation to be a falsehood.

A representative sampling of the many uses to which simulation has been applied and the contributions it has made to E-3A system development is presented in Section 2. In general, all of the models and simulations used on the E-3A program have been deterministic or Monte Carlo mathematical formulations written in the FORTRAN programming language for various high-speed computers. Their sizes have ranged from a few lines of code to several thousand. As an example of a current application of simulation that benefits the operational E-3A fleet today, a brief description of the E-3A Mission Simulator is also provided.

Several valuable lessons concerning modeling and simulation have been learned over the course of E-3A development. These lessons highlight certain important truths about modeling that must be understood and accounted for when developing any avionics or C^3 system. These truths are discussed in Section 3.

1.2 E-3A Program Summary

The E-3A is the result of almost fifteen years of concerted effort. In the mid-1960s the Overland Radar Technology Program was established by the United States Air Force to determine the feasibility of overland radar techniques for long-range surveillance of low-flying aircraft. As a result of this feasibility program, which succeeded in identifying two promising pulse-doppler radar techniques, one by Westinghouse and one by Hughes, the Air Force prepared a Concept Formulation Package for the E-3A Airborne Warning and Control System (AWACS) program. This package was approved by the Department of Defense in late 1967. The Contract Definition Phase was authorized in 1968 with the stipulation that a full-scale radar demonstration be given before full program approval. The Boeing Company was awarded the prime contract in July 1970. The contract was divided into three phases: Brassboard, full-scale development, and production.

The purpose of the Brassboard phase was to demonstrate that an airborne radar could have an operationally useful overland surveillance capability. From March through August 1972 a competitive fly-off was conducted between the two pulse-doppler radars under consideration, and in the fall of that year Westinghouse was selected as the E-3A radar contractor. An airborne tracking demonstration was then conducted with the winning radar in late 1972. This was followed by several additional demonstrations in the United States, culminating in the first E-3A demonstration in Europe in April 1973.

The first segment of the full-scale development phase, the System Integration Demonstration (SID), was successfully completed in September 1974. The Brassboard aircraft and radar were retained and production prototypes of most of the other E-3A mission avionics equipments were added. This formed a single-thread system to demonstrate the basic functional capabilities and to show that the various mission avionics elements could be integrated into a smoothly working system. Following a series of special tests in the United States, the SID E-3A was deployed to Europe for a demonstration to senior NATO defense officials and military personnel in April 1975. Successful completion of the SID test program demonstrated that the principal high-risk factors had been resolved and production authorization was recieved.

The remainder of the development program dealt with the system testing and qualification of the production configuration which was developed in 1975-1976. Three test aircraft for this phase underwent rigorous testing in 1976-1977 with participation by Air Force and contractor personnel. The first production aircraft was delivered to the USAF Tactical Air Command at AWAC Wing Headquarters, Tinker AFB, Oklahoma, on 24 March 1977. As of September 1979, nineteen of the total programmed force of 34 E-3As have been delivered.

The production E-3A system avionics (figure 1) include a surveillance radar and IFF processor; navigation equipment; a high speed data processor; nine multipurpose and two specialized display consoles; and a variety of UHF, VHF, and HF communications equipments. The airframe is a modified Boeing 707-320B. With a mission crew of thirteen, the E-3A is designed to provide timely detection, tracking, and identification of aircraft within its surveillance volume, data communication of this information to external elements, and military command and operational control of friendly aircraft.

An E-3A enhancement program was established in 1974 to augment the E-3A's already substantial capabilities. The currently approved program consists of the incorporation of a Joint Tactical Information Distribution System (JTIDS) capability for high-capacity, jam-resistant digital communications, a maritime-surveillance capability for detecting and tracking ships, an expanded C^3 capability involving the addition of several radios and central-processor capacity, and other minor system enhancements and product improvements.

NATO is procuring eighteen enhanced E-3A systems as part of its advanced Airborne Early Warning force. Delivery of the first NATO E-3A is scheduled for early 1982, with subsequent deliveries over the following three years.

2. APPLICATIONS OF MODELING AND SIMULATION DURING E-3A DEVELOPMENT

2.1 Detailed Subsystem Design

The heart of the E-3A system and its greatest technological achievement is its surveillance radar, which must pick out low-flying aircraft from ground clutter over an area of thousands of square miles. Key advances were made in developing the radar in the areas of ultra-stable signal generation and digital processing. In addition, the narrow-beam signal with its low antenna sidelobe characteristics – which are necessary for accurate target detection overland – was achieved through a significant advance in the design of the radar antenna. Lastly, the low sidelobe characteristics of the transmitted energy pattern and, hence, the high performance of the radar, were sustained through the use of a sophisticated antenna shield or radome designed to very precise tolerances. Several special-purpose computer simulations assisted substantially in the process of designing these major subsystem components.

2.1.1 Radar Subsystem Design

In the design of the Westinghouse radar, much of the general design approach (figure 2) from the receiver through the signal processor to the radar data correlator was defined in the late sixties by design tradeoff studies using detailed contractor simulations. In 1968 several individual simulations of parts of the radar were combined into one end-to-end simulation program, appropriately called the Long-Form Radar Simulation. By simulating, pulse-by-pulse, the entire radar signal processing sequence from RF input to digitized, correlated output, the Long-Form simulation was used, first, to explore the various hardware design alternatives, then to refine and optimize the design alternative chosen. This design-and-refine process encompassed both the hardware configuration and the target detection algorithms that would reside in the radar subsystem software.

The Westinghouse Long-Form simulation was, as one might expect, a very large program. It was programmed originally for the UNIVAC 1108 computer and took 100-200 times longer to run than the radar takes to operate in real time. It has been updated over the years, converted to newer machines, and even now is used in the continuing effort to extend and optimize the radar's capabilities. Parts of the program have been borrowed for other uses, such as cost-reducing design tradeoff studies and production-unit performance evaluation, replacing certain time-consuming and costly acceptance tests.

2.1.2 Antenna Design

In the design of the low-sidelobe antenna, a detailed performance simulation was developed by Westinghouse to determine what the antenna's electromagnetic and mechanical properties should be. The antenna (figure 3) consists of a planar array of slotted waveguides, or "sticks," mounted horizontally across the aperture. These sticks are then manifolded through a series of waveguide coupling devices back to a common input port. The dimensions of the sticks, the configuration of the array, and the manifold coupling design determine the distribution of radiated energy and, consequently, its mainbeam and sidelobe structure. The antenna simulation model was used to specify the optimum dimensions, configuration, and coupling design to a very high degree of accuracy. It utilized propagation theory, circuit modeling, and other analytical techniques to achieve the required accuracy. The inclusion of electromagnetic coupling effects among the waveguides was the largest single contributor to the subsequent agreement between predicted and measured pattern results. It was also largely responsible for the cost-effective antenna design program.

In addition to the analytical design simulation, a mechanical design simulation was developed to follow through in the manufacturing of each antenna to ensure conformity with the stringent tolerance requirements. Even the machining process was controlled by computer.

2.1.3 Radome Design

In the design of the radome, or protective bubble for the antenna (figure 4), a ray-tracing computer model was developed by The Boeing Company to predict the radar signal transmission, reflection, absorption, and phase delay resulting from various radome designs. These are the principal factors affecting the radar sidelobe levels and, ultimately, the performance of the entire radar subsystem. The design parameters included in the model consisted of radome shape, size, wall construction, antenna configuration and location, operating frequency, and several electromagnetic design constraints. One of the most obvious issues to resolve during this time period was whether to mount the radome/antenna over the fuselage or on the tail. Through the use of the ray-tracing computer model (and extensive wind tunnel tests) an acceptable fuselage-mounted radome was derived in 1970 and subsequently verified by scale-model radiation pattern measurements.

This original radome was of uniform thickness. Continued study, simulation, and pattern measurements resulted in an improved version in 1972 that was tapered discretely in thickness. When in 1975 it was found that residual radar sidelobe clutter in certain regions was still higher than desired, a radar simulation developed by MITRE – the Air Force's System Engineer for the E-3A – was used to isolate the cause. Measured radiation patterns representing the antenna alone and the antenna with radome were separately fed into the simulation, and the additional sidelobes were found to result from specific areas within the radome. Ultimately, this led to a radome-improvement program which, when completed in 1981, will yield a 90 percent reduction in the radar signal losses attributable to the radome. This, in turn, will result in a significant increase in the E-3A surveillance capability.

2.2 Radar Performance Prediction

Especially during the early phases of system acquisition it was important to be able to predict how well the radar would perform. The radar was the largest single technical risk; look-down surveillance over land was never before possible. There was some skepticism that this latest attempt would be successful. Yet performance prediction over a sufficiently broad range of operational situations was no easy task – in fact, without simulation it was not possible.

Two types of simulation were required to allow adequate performance prediction. One was the detailed simulation of the phenomenology involved in transmitting large amounts of radio frequency radiation through the atmosphere, onto the ground as well as low-flying aircraft, and back through the atmosphere into the receiver. The second type of simulation was a higher level, shorter version of the Long-Form Radar Simulation that would permit extensive analysis and assessment of system-level performance in larger, scenario-type simulation models.

2.2.1 Phenomenology Models

In the phenomenology area, several models were developed. One was an atmospheric refractivity model, originally developed to study propagation effects on surveillance coverage. Another was a ground clutter prediction model for studying the various types and mechanisms of radar signal backscatter. A third was a clutter transient model for studying the potential effects of transient waveforms at various filters in the receiver. These models, or key parts of them, were then incorporated into several subsequent models; most importantly, the system contractor's Surveillance Function Simulation Model, which also utilized the second type, the Short-Form Radar Simulation.

2.2.2 Surveillance Function Models

The Short-Form simulation was designed by Westinghouse to be the functional equivalent of the detailed Long-Form program. However, it would run rapidly enough to provide scan-by-scan radar output data that could be used as direct input to an E-3A central processor model of extended system functions, such as tracking aircraft over many minutes of real time. Westinghouse used the Short-Form simulation first to optimize the operational radar parameters that would reside in software, such as the beam pointing angle and the angular offset between the pulse-doppler and pulse beams. Secondly, approaches were explored for managing in the software the many different radar modes that can be selected for use in different surveillance directions (or sectors).

Boeing used the Short-Form simulation to define and optimize the interface between the radar and central processor subsystems and to develop target tracking algorithms for use in the eventual airborne operational computer program. There were minor feedback effects from these system-level studies on the radar hardware and software design, as the overall performance of the target tracker was iteratively brought up to specification levels.

Boeing's initial tracker choice during the latter part of the Contract Definition Phase in 1970-1971 was called a "ρ,θ" tracker, because the principal state variables used were target range (ρ) and azimuth angle (θ) relative to the E-3A. Target speed and heading relative to a fixed reference direction (i.e., North) were also used. This approach was used because it allowed straightforward integration of the target tracking functions. Studies using the Surveillance Function Simulation, however, indicated that this approach led to some fairly complex computational algorithms. For example, eight different smoothing coefficients were required, instead of the four required in the old U.S. Semi-Automatic Ground Environment (SAGE) system tracker. In addition, the ten unique elements of the filter covariance matrix would have to be updated each time the track was smoothed or extrapolated. A Cartesian ("x,y") approach was found to provide superior performance while imposing less demanding computational requirements. These and other modeling studies resulted in an early decision by Boeing to discard the ρ,θ tracker in favor of the x,y tracker. Continued modeling studies over the next few years resulted in additional refinements to the tracker design.

2.2.3 Radar Performance Prediction Models

Boeing's Surveillance Function Simulation was needed for radar design tradeoff studies and operational software (e.g., tracking) development and validation. At the same time, the Air Force (through MITRE) needed to predict surveillance performance to better assess the system's potential contribution to Air Force operations. A variety of simulations which could accurately predict E-3A radar performance in terms of detection range against various radar cross section targets were developed, improved, and refined by MITRE, beginning with some theoretical models in 1968.

The first of the E-3A radar performance prediction programs to be developed were a group of Airborne Moving Target Indication (AMTI) programs developed in the late 1960s. Their purpose was to permit performance prediction for a variety of potential pulse-doppler radar designs against a variety of aircraft target types and under a variety of simulated operating conditions. The program design approach was to develop groups of subroutines, or modules, that could be selected to operate with any of a group of main programs (figure 5). Seven main programs were developed to provide the analyst with flexibility and selectability for assessing various radar design techniques, some more sophisticated than others.

The premise was that if the reflected radar energy from the target, the reflected energy from other sources (i.e., clutter), and the receiver noise level were known, a fairly accurate prediction of the probability of target detection under these conditions could be made. The factor with the greatest uncertainty in such a prediction was the amount of clutter energy that would compete with the target return signal. Since there was no test radar then with which to accumulate flight test data on the expected clutter levels over various types of terrain, the AMTI clutter models had to be totally theoretical. Nevertheless, performance predictions using the AMTI programs were reliable enough to provide valuable insight into the general levels of performance that could be expected with various radar designs under various conditions.

In 1969 portions of the AMTI programs were incorporated into an E-3A/target aircraft trajectory simulation program to predict E-3A radar detection capability in various mission scenarios. The theoretical clutter models were still required and, consequently, the accuracy of the simulation results was somewhat unclear.

The radar performance and trajectory program was revamped in 1972-1973 when E-3A Brassboard Program flight test data became available. The data was gathered and tabulated to provide target detection probability as a function of target azimuth off the E-3A centerline axis, target velocity, and signal-to-noise ratio for flight over different types of terrain. In essence, the effect of actual ground

clutter was built into the data and realistic and accurate performance prediction was, for the first time, possible. After adding what amounted to real clutter data on a "standard target," which could be scaled analytically for any target at any range, more improvements and sophistications were made to the radar performance prediction program over time. Better models for estimating atmospheric losses were incorporated into the analytical portion of the simulation. Also, radar cross section routines for various Soviet and American aircraft were added for estimating radar performance against specific aircraft. Simulation results were found to be quite close to the corresponding flight test results that could be obtained.

The radar performance program was again improved and updated in 1976-1977 when development program radar flight test data became available. Increased sophistication was incorporated into the program in terms of radar modes, calibration and scaling constants, system losses, and minute beam-spreading and refraction effects caused by the radome. This increased sophistication was made possible by comparing the simulation results with the flight test data and refining the simulation design.

Even now the radar performance program continues to be improved and updated. The latest improvement has been the incorporation in one version of a series of field measurements of antenna/radome gain variation with azimuth. Work is also ongoing to refine the estimates of certain range- and altitude-dependent system losses for even more precise performance prediction.

2.3 System Advocacy

A number of critical issues have arisen over the course of E-3A system development. In addition to early uncertainties regarding the viability of an effective overland surveillance capability, there were concerns for the survivability of such a system in a wartime environment. Its effectiveness, resistivity to jamming, and the force size required to satisfy worldwide needs were questioned. In addressing these concerns, flight tests or exercises were not possible because the system was not then developed. Analysis supported by simulation and modeling was the only available alternative.

2.3.1 Survivability

In 1971 the U.S. Department of Defense (DoD) directed that a study be made of the survivability of an AWACS in a European conflict situation and that the sensitivity of the results be related to radar performance against likely threat aircraft. Three computer models were required for that study.

As expected, the radar performance model was a key one. During the initial phase of the study, before the Brassboard radar data was available, theoretical radar performance against representative threats was all that was available. Consequently, the study emphasis was on the warning time and defensive support that could be realized over a broad range of aircraft detection ranges. After Brassboard results became available in late 1972 and 1973, specific detection predictions were made and the corresponding warning times and defense levels could be estimated.

A second, rather simple but effective model, which assisted in illuminating the issue of defensive fighter support for the E-3A, was the Fighter Commit Envelope Model. Requiring only a dozen lines of code, this model used the geometric relationships of distance and time between constant velocity vectors representing a hostile penetrator and friendly fighter to determine the locus of points in the horizontal plane where the defending fighter could reach a terminal engagement situation on the penetrator before the penetrator could reach a terminal engagement situation on the E-3A (figure 6). The appeal of the approach was that the size of the envelope depended primarily on the E-3A detection capability against the penetrator, rather than on the weapons capabilities of the respective aircraft, which were subject to debate. Because of the eventual predictions that the E-3A detection capabilities against threat aircraft would be substantial, and that the resulting areas, or commit envelopes, from which fighters could be drawn would be large, it was recognized that the E-3A could provide the single most important ingredient both for its own defense and the defense of other friendly assets in time of attack: warning time to react.

For those who insisted on quantitative estimates of the probability of E-3A survival against attacks by various numbers of hostile aircraft when defended by various numbers of friendly fighters, a Probability of E-3A Survival Model was developed. This short mathematical model of a couple dozen FORTRAN statements required estimates of the cumulative kill probabilities of hostile aircraft against an E-3A-size aircraft and friendly aircraft against the hostiles. Since published data on such probabilities tended to be overly specific and not totally applicable, the model was programmed to generate results parametrically over a range of probabilities. In the end, because few could agree on the kill probabilities that should apply, the parametric approach proved most appropriate.

2.3.2 Mission Effectiveness

In the general sense, mission effectiveness has been a top-priority item in the design of the E-3A system from the beginning. In 1973, however, DoD specifically asked for assurance of system effectiveness in the European environment before system development could continue. A large-scale air-battle simulation model, called TAC PENETRATOR, was selected by the U.S. Air Force staff for analysis and assessment of E-3A mission effectiveness. The simulation was run with and without the E-3A to show improvement resulting from its superior surveillance, communications, and command-and-control.

The TAC PENETRATOR model is an expected value model that uses a series of 53 simultaneous differential equations to compute the interactions and outcome of a tactical air battle. The model uses a notional approach and describes a group of RED aircraft attacking a group of BLUE assets defended by a group of BLUE SAMs and a group of BLUE fighters (figure 7). The major simulation output is the usual measure of effectiveness of RED bombers on BLUE targets, in addition to statistics regarding RED aircraft killed, BLUE aircraft killed, and SAMs and C^2 centers destroyed.

At the risk of upstaging one of the lessons learned in applying modeling and simulation, comprehensive air battle simulations like this one have generally lacked credibility for a number of reasons to be discussed later. In this particular case, however, the results obtained were considered adequate for addressing the concerns of the then Deputy Secretary of Defense because the model had several major conservative assumptions built into it. For example, there were no hostile aircraft aborts; there was effective RED ground-control-intercept (GCI) coverage in BLUE territory; and RED kill probabilities against BLUE ground targets were unity. The conclusion was that, since the predictions of improvement were so conservative, they were that much more believable.

2.3.3 Electronic Countermeasure Resistivity

In 1974 the U.S. Senate Armed Service Committee Report on the FY75 Authorization Bill requested that the Secretary of Defense appoint a group of independent radar and electronic countermeasure (ECM) experts to examine in detail prior to any production decision the ECM resistivity of the E-3A radar. In response to this request the Director of Defense Research and Engineering (DDR&E) appointed such a group in August and directed that the ad hoc committee report be completed and submitted to the Secretary of Defense and to the Defense Systems Acquisition Review Council (DSARC) by the beginning of December. Air Force/MITRE simulation results were a significant factor in the Committee's favorable assessment.

A radar performance in ECM simulation was developed by MITRE to produce target detection range plots as a function of azimuth angle for one or more E-3As in a scenario containing multiple noise jammers. Fixed and moving jammers could be specified, with the detection range results recalculated every so-many minutes. An illustration of a typical simulation output is provided in figure 8. The model assumes a constant (nose-on) cross section for the target class and determines the effect of multiple noise jammers on E-3A detection range by an algebraic formulation involving the detection range without jamming and the jammer-to-noise power density ratio. Although the theory employed in the model is straightforward, the program itself is fairly large, with one main program and eleven subroutines to determine the precise values to be used in the formulation. The model's prediction capability has been confirmed by a number of jammer flight tests that have been conducted since the time of its development.

The radar performance in ECM simulation model has been used extensively since 1974 to evaluate additional ECM threat projections. The model results have provided keen insight into the relative effects of alternative jammer tactics and the merits of various electronic counter-countermeasures that may provide protection against such tactics.

2.3.4 Force Sizing

The number of E-3As required to support various surveillance missions has been difficult to quantify precisely without a force sizing computer model. In the late 1960's, during Contract Definition, 64 E-3As were planned based on Air Force paper analysis of the number required to do substantial perimeter surveillance of the continental United States for air defense and to do limited tactical surveillance worldwide. In 1970 the total number of E-3As was reduced to 42 as part of a DoD-wide budget cut. In addition, the Air Force had to rethink the allocation of E-3A resources because the focus of E-3A employment was shifted from U.S. air defense to general purpose worldwide applications. Lack of an adequate analytical tool for providing DoD and congressional decision-makers with insight into the need for a force of this size may have contributed to another cut in the E-3A program in 1973 to 34 aircraft. It was in 1974 that the first E-3A Force-Sizing Model became available for Air Force studies and analysis.

The E-3A Force-Sizing Model is a Monte Carlo computer program that determines the number of E-3As required to provide various levels of on-station coverage. The program models a scenario consisting of a ground operating base and one or more airborne orbits (or stations). The simulation includes the fly-out from base to station, the on-station coverage, the return to base, and the ground refueling and maintenance prior to another mission (figure 9). In-flight aborts, as well as the variability in ground turnaround time, are modeled statistically. The program outputs the on-station coverage that can be expected for the given base-to-station distances as a function of E-3A force size. In recent years the model has been generalized to project force-sizing requirements for any aircraft of known characteristics.

The Force-Sizing Model has been used in design-tradeoff studies of reliability and maintainability, in employment studies to determine the number of aircraft per orbit to satisfy various mission requirements, and in basing studies to assess the effects of various fleet basing alternatives on force-sizing requirements.

The Force-Sizing Model proved to be a valuable tool in 1975 when the NATO Supreme Allied Commander, Atlantic (SACLANT) expressed interest in the E-3A as a NATO Airborne Early Warning system. One of his concerns was whether the E-3A could fulfill specific surveillance coverage requirements with the allowable number of aircraft. Force-sizing model results helped convince him that it could.

2.4 Dispelling an Early Fear: Terrain-Screening

Another timely application of simulation showed that a seemingly obvious fact about an airborne radar was actually a falsehood, that an early fear and potentially serious concern were unfounded. The issue arose in 1967 when a cursory attempt was made to estimate the effect on airborne radar coverage of screening by terrain. The single case of a stationary E-3A looking in one azimuth direction was considered. The conclusion was that the line-of-sight range to a target aircraft would be reduced as much as 40 percent for the situation where it was terrain-following through mountains. Naturally, this result was disappointing and concern arose regarding the utility of airborne radar in mountainous areas. This concern was particularly insidious because many people accepted the conclusion without question, believing it to be rather obvious. Fortunately, not everyone accepted it because it was not based on any detailed or extensive analysis of terrain-screening effects over real terrain.

In 1970 a Terrain-Screening Simulation Model was developed by MITRE. The model approach was to determine whether a point at a given range and azimuth is screened from an observer position (on the ground or in the air) by terrain along the line-of-sight. The terrain distribution was approximated by dividing a geographic area into a large number of grid rectangles with sides of constant latitude and longitude. At each corner coordinate the height of the terrain was specified as a terrain data point read in by input card. The size of the grid rectangles could be varied, depending on the accuracy desired and the irregularity of the terrain. The height at any location was determined by finding which grid rectangle the point was in and employing a linear estimation technique based on the terrain heights of the four corner points. Refractivity of the atmosphere was approximated by a 4/3 earth radius.

The Terrain-Screening Model was applied satisfactorily to the mountainous terrain issue in 1971. Detailed analysis was conducted for a number of potential penetration routes into the U.S. over mountainous terrain. The terrain height in the appropriate areas of Alaska and Canada was determined from terrain maps. The results indicated that there were no penetration routes that would result in as drastic a reduction in surveillance as the 40 percent projected by the 1967 stationary observer analysis. The reason was that the motion of an E-3A resulted in rapid changes in the terrain distribution, and continuous screening along a given penetration route was not possible. Another result was that the amount of screening was reduced dramatically as the target height increased. Thirdly, the study results showed that any effects of terrain-screening on long-range, low-altitude target detection could be minimized by computer analysis of the best E-3A orbit locations with respect to a specific mountain range. Lastly, it was effectively shown that multiple E-3As with

overlapping coverage reduced the effect of terrain-screening substantially further to the point where the impact would be minimal. In essence, what was considered to be an obvious truth and an unfortunate fact of life for airborne radars was shown to be false at a time when program efforts had to be focussed on other more important concerns and system development issues. Subsequent experience during E-3A flight tests in the vicinity of mountains tells us that the Terrain-Screening Model results were correct.

Over the last several years more precise terrain height data for certain parts of the world has gradually become available on computer magnetic tape from the Defense Mapping Agency. In 1978 the capability to read and sort this data was built into the Terrain-Screening Model. Other improvements and refinements were also incorporated in the model design. It is now possible to use the model for high resolution terrain-screening analysis of geographic areas for which data is available, such as Central Europe. An illustration of the kind of output than can be obtained is provided in figure 10. The case analyzed was for points on the ground, rather than for aircraft above the ground.

2.5 An Operational Application: The E-3A Mission Simulator

A current application of simulation on the E-3A Program is the Mission Simulator. The simulator is a facility at the E-3A Main Operating Base at Tinker AFB (figure 11) wherein E-3A mission crew members may be trained as an interactive and entire crew in an operationally lifelike environment. It consists of an instructor area with three multipurpose consoles and four communications simulation consoles, and a mission crew area with nine multipurpose consoles, a computer operator's console, and other display and processor equipments, laid out like an E-3A aircraft. The instructors control the data being displayed on the trainee consoles and provide simulated voice communications with the external environment. They also monitor and assist the trainees in their development.

The simulation software consists of the major portions of the E-3A Airborne Operational Computer Program (AOCP) for processing mission data and operator switch actions, and a full repertoire of simulated data: radar and IFF reports, navigation data, digital communications information, electronic countermeasure information, and a number of selectable scenario data bases for added realism.

The Mission Simulator is used to train new crew members in as controlled an environment as possible, under close monitor supervision, prior to actual flight training onboard an E-3A aircraft. It is also used to replay and analyze actual missions; data from every mission is recorded on magnetic tape in-flight. The simulator has even greater capability in one sense than the real thing because the action can be frozen in time for analysis or explanation.

In addition to the Mission Simulator is an individual position trainer (IPT) facility, which is used to train operators in the use of the multipurpose console before being graduated into a full crew environment.

3. LESSONS LEARNED

The many applications of modeling and simulation over the course of E-3A development have provided opportunities to recognize several important truths. Perhaps the most important is that, no matter how realistic and accurate a model is, it will never be as believable to decision-makers as actual system tests or demonstrations. As a result, simulation plays a less important role the further into a program it is, as more test data becomes available.

The many applications of modeling and simulation have also taught several important lessons. Three are most significant:

1. **Large models are not necessarily better than small models and small comprehensible models are always better than large incomprehensible ones.**

As discussed in the area of survivability, a small and rather simplistic interceptor availability model was perfectly adequate in the early 1970s for showing that the E-3A could be protected with interceptor aircraft. Data on the respective kill probabilities of hostile and friendly weapons systems was subject to debate; consequently, modeling the endgame was inappropriate. The effectiveness of this approach was in sharp contrast with the ineffectiveness of a separate attempt in those days to use the output of a large, detailed intercept simulation to make the same point. This model had been obtained from a contractor and it provided very detailed results. The problem was that each model run also produced certain curious results, and an inordinate amount of time was required to determine how they could be rationalized. Eventually the model had to be discarded.

A pitfall of using large-scale simulations is that they may give the illusion of modeling things to great levels of detail when the input data is not adequate to justify such detail. This is similar to the problem of significant figures, where the result of multiplying several numbers together is only as precise as the least precise number being multiplied. Sometimes detailed simulation is not even possible. Occasionally not enough is known about the cause-and-effect relationships involved in some process to model it. Perhaps most difficult is recognizing this situation and biting one's modeling tongue. A better approach is to develop a number of smaller models for those parts of the process that are well understood. The results from these models can then be tied together as much as possible under the circumstances by the reasoning power or common sense of the analyst.

2. **Application of large, existing models to new problems is usually difficult and must always be done with great care.**

Usually, the larger the model the more specialized it is, no matter how hard the model developer attempts to make it general. In 1973, for example, a large-scale computer program simulating a European air war was obtained and adapted for some E-3A effectiveness studies. It was discovered in short order, however, that the program would have limited utility for the task at hand because major programming changes would be required to add a second E-3A to the simulation.

The best hedge against overly specialized simulations is to make them as modular as possible. This was done effectively with the E-3A Long-Form Radar Simulation and the Radar Performance Prediction Models, beginning with the AMTI routines mentioned previously.

Parts of the Long-Form program and several of the AMTI routines are still in use today. Rather than attempting to force a new problem to fit an old model, the more effective approach has been to develop a specific executive or main program that will call all required modules, some of which may have to be developed specifically for the problem at hand.

A cardinal rule for developing simulations that are to be saved for future use is to document them fully. Many models are developed by people who leave the project or, worse, the company, without documenting their work. These models are then useless unless someone can be given time to explore them thoroughly and document them, if this is even possible, depending on the transparency of model design.

3. **Large, multi-system effectiveness models are the least credible of all models because they are the most difficult to apply correctly.**

Of all the models and simulations used during the E-3A program, the large-scale, multi-system effectiveness models had the least utility. One or more of the requirements for successful application of this type of model were usually violated.

One requirement is that all model constraints and assumptions be well understood and the caveats advertised widely. Also, the sensitivity of the results to changes in the assumptions must be known for the results to be meaningful. One analysis of E-3A effectiveness conducted in 1973 at first encountered criticism because enemy ECM was not adequately modeled. Upon further analysis, however, this was found to be a conservative assumption in terms of the model's measure of effectiveness: the improvement in surveillance and C^3 due to the addition of the E-3A. The reason was that the E-3A is far less susceptible to ECM than other systems of its class that comprise the C^3 network. Surprise, concern, and debate could have been avoided by widely advertising the model ground rules and assumptions.

Another requirement is that every model mechanism and algorithm be understood and judged appropriate. Sometimes the inappropriateness of a particular algorithm in a model, particularly in a large model, can go unnoticed, i.e., if the results are not contrary to common sense. In this situation the analysis is worthless, but no one knows it. In most cases, fortunately, the process of varying the input parameters and conducting sensitivity analyses uncovers those hidden lapses from reality. In 1972, for example, a large-scale war game simulation was used to determine the improvement in the outcome of a battle as a result of the introduction of the E-3A. To everyone's surprise the outcome was worse. It seemed that additional warning time was not a good thing. More detailed analysis revealed, however, that the interceptor allocation algorithm was inappropriate. Consequently, the greater the warning time the sooner the allocation and the worse the outcome.

Perhaps the most fundamental requirement for successful use of systems effectiveness modeling is that the model's measures of effectiveness be appropriate to the problem at hand. One E-3A effectiveness study, for example, was substantially handicapped because the model used measured the C^3 effectiveness of an isolated E-3A versus that of the ground C^3 environment. The proper measure should have been the complementary effectiveness of a combined E-3A/ground environment capability versus the capability of the ground environment alone.

Another effectiveness study employed a model that listed as one of the key measures of effectiveness the number of hostile fighters killed versus the number of friendly fighters killed. Addition of the E-3A in certain scenarios resulted in a decrease in the number of hostile fighters killed and an increase in the number of friendly fighters killed. By the above measure of effectiveness, this would have meant addition of the E-3A was counterproductive. It turned out, however, that the number of hostile fighters killed decreased because the more effective surveillance and C^2 provided by the E-3A permitted more friendly fighters to avoid intercepting hostile fighters to conserve their weapons for use against hostile bombers and fighter-bombers. The number of friendly fighters killed increased because considerably more of the fighters were brought into the conflict as a result of the earlier warning provided by the E-3A. The measure of effectiveness, therefore, was misleading and inappropriate.

4. CONCLUSIONS

This paper has presented just a sampling (summarized in figure 12) of the various applications of modeling and simulation to the development of the E-3A. Many truths concerning the modeling and simulation process were made apparent and many lessons were learned. Yet the most encompassing truth clearly stands out -- models and simulations are necessary and important tools in the development of any avionics and C^3 system.

They can be used for such diverse applications as subsystem and system design, performance prediction, system advocacy, and even crew training. If used carefully and prudently, modeling and simulation can provide a crucial service in the system design process and, in addition, fill many of the knowledge gaps encountered along the development path.

Figure 1. E-3A Interior Layout

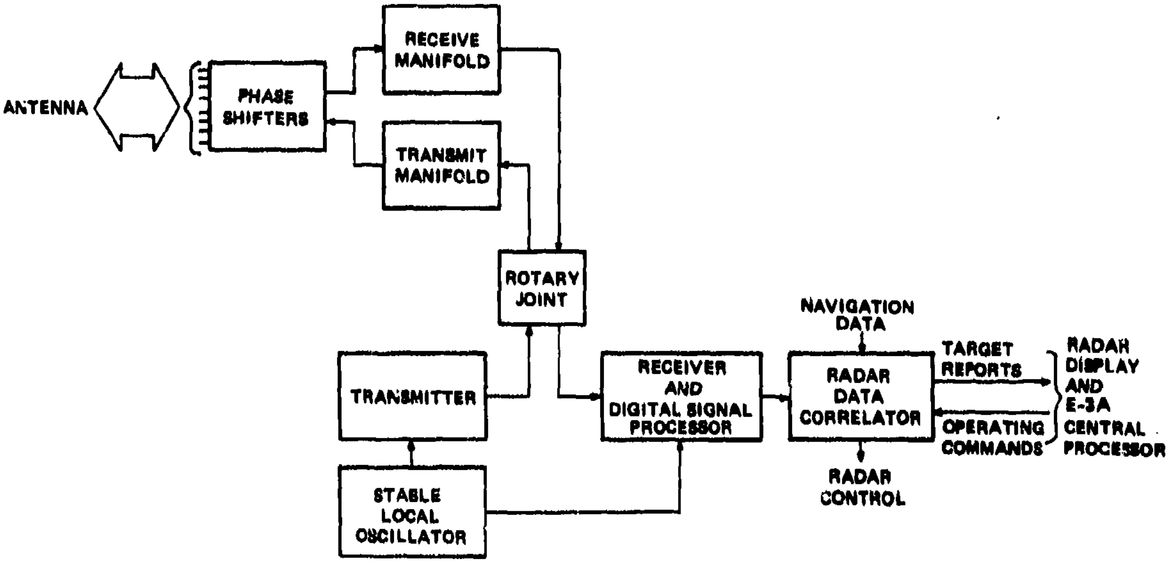


Figure 2. Block Diagram of E-3A Radar Design

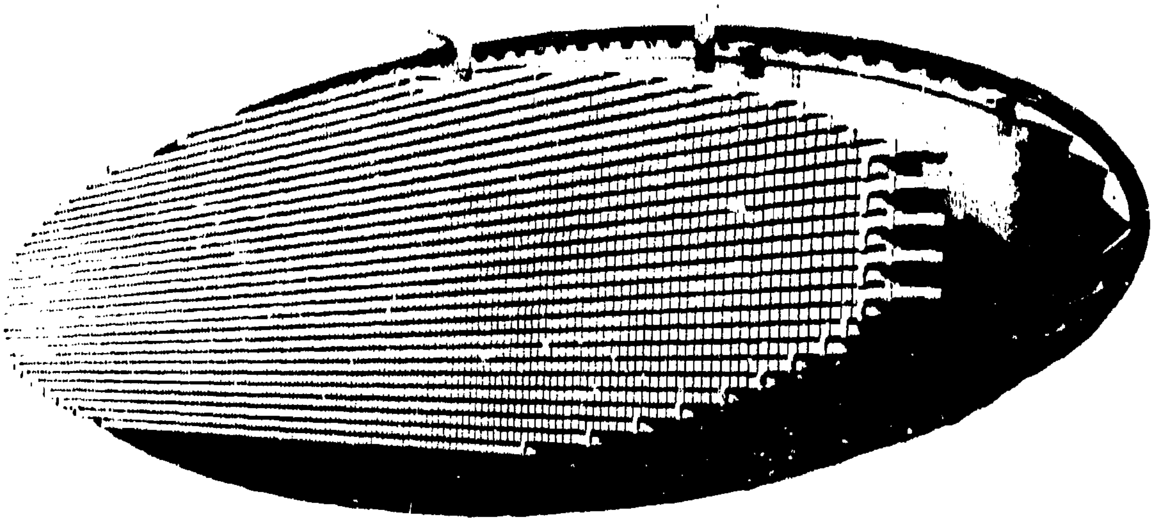


Figure 3. Antenna Array Face

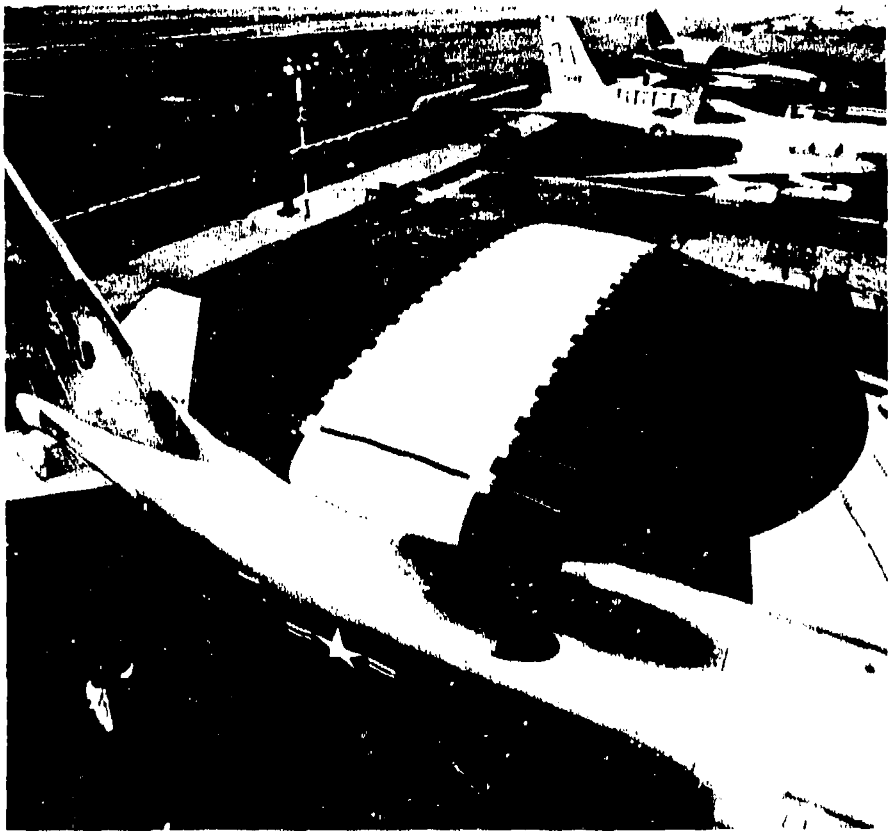


Figure 4. Close-up View of E-3A Radome

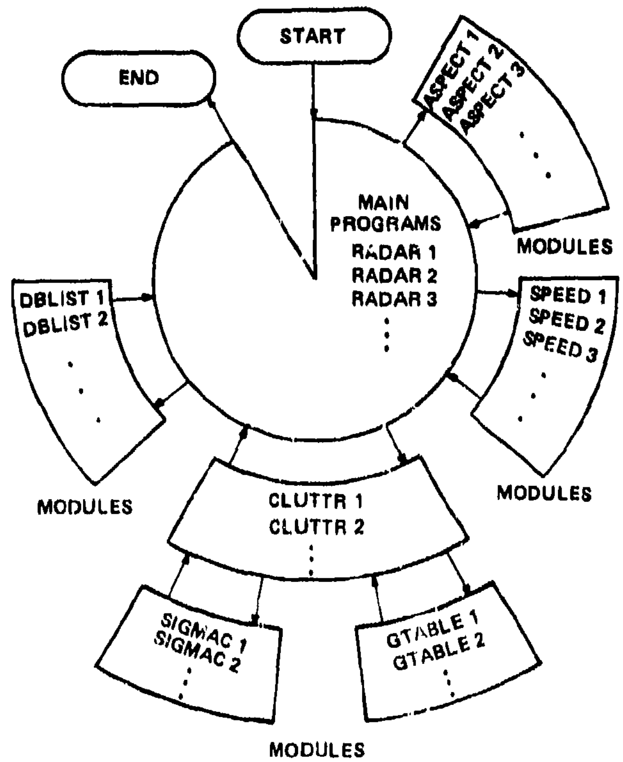


Figure 5. AMTI Program Modular Design

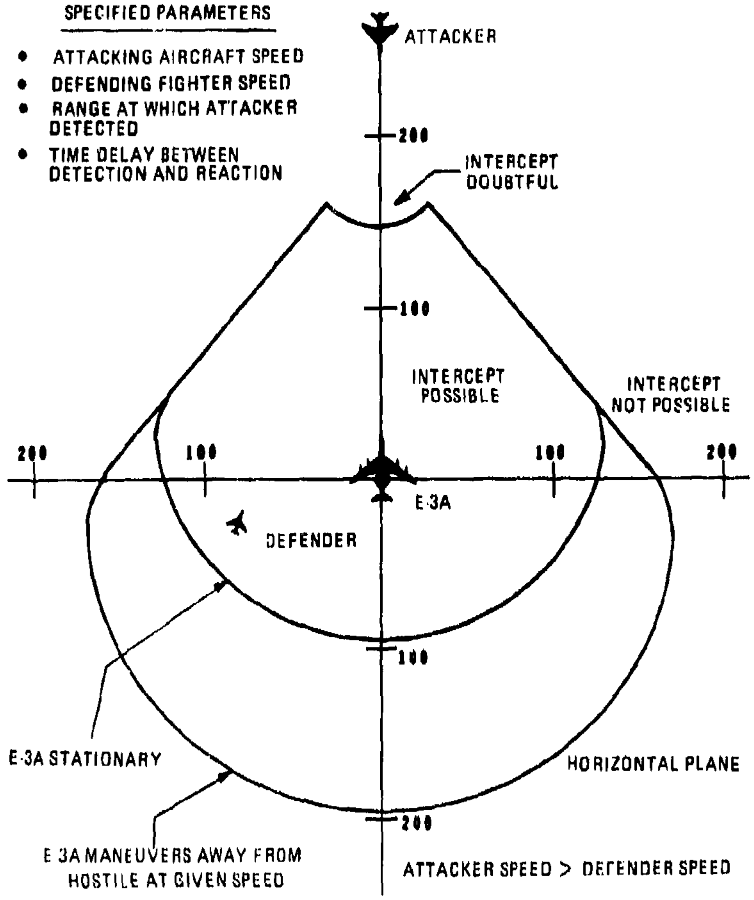


Figure 6. Illustration of Fighter Defense Envelope

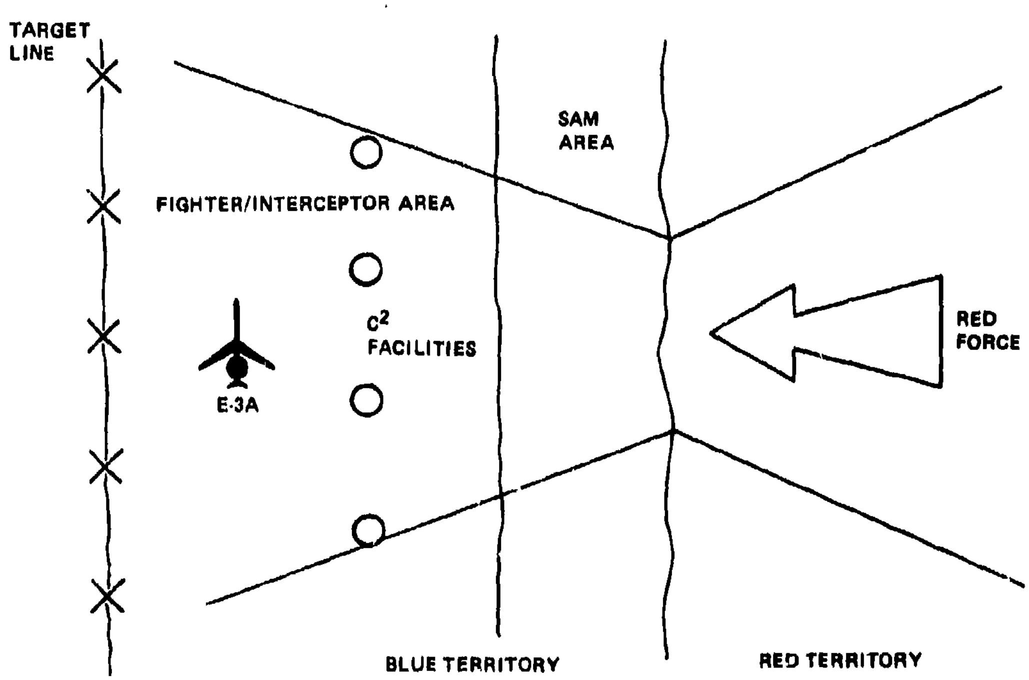


Figure 7 Notional Approach of TAC PENETRATOR Model

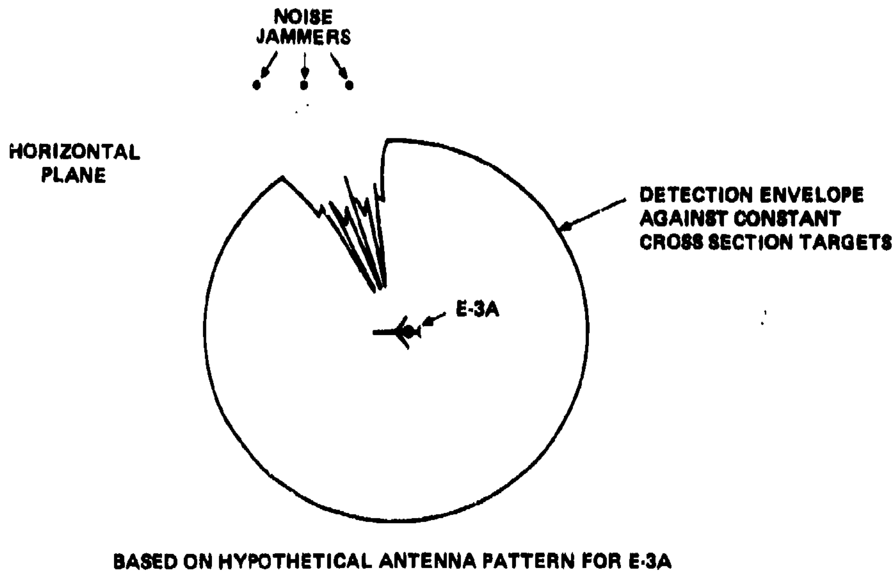


Figure 8. Illustration of Performance in ECM Program Output

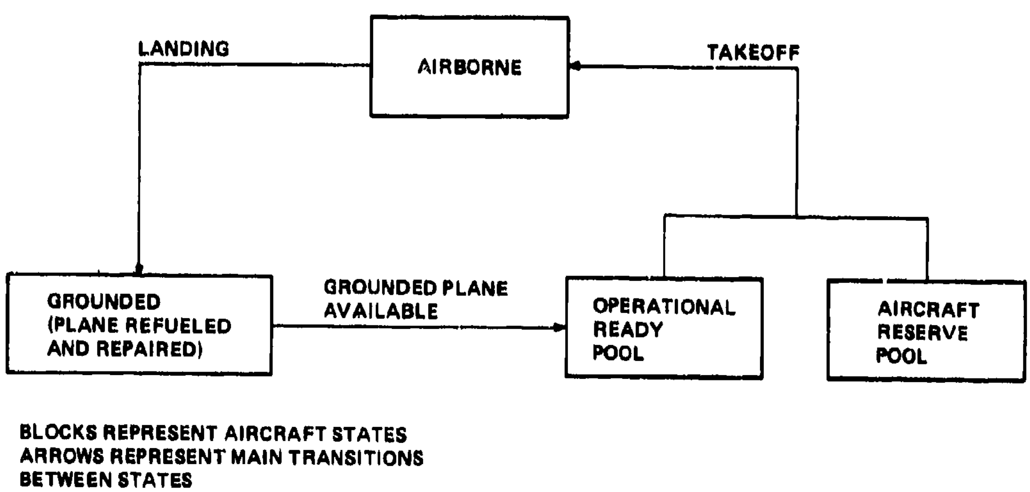


Figure 9. Force Sizing Model Design

Figure 10. Sample Terrain-Screening Model Output

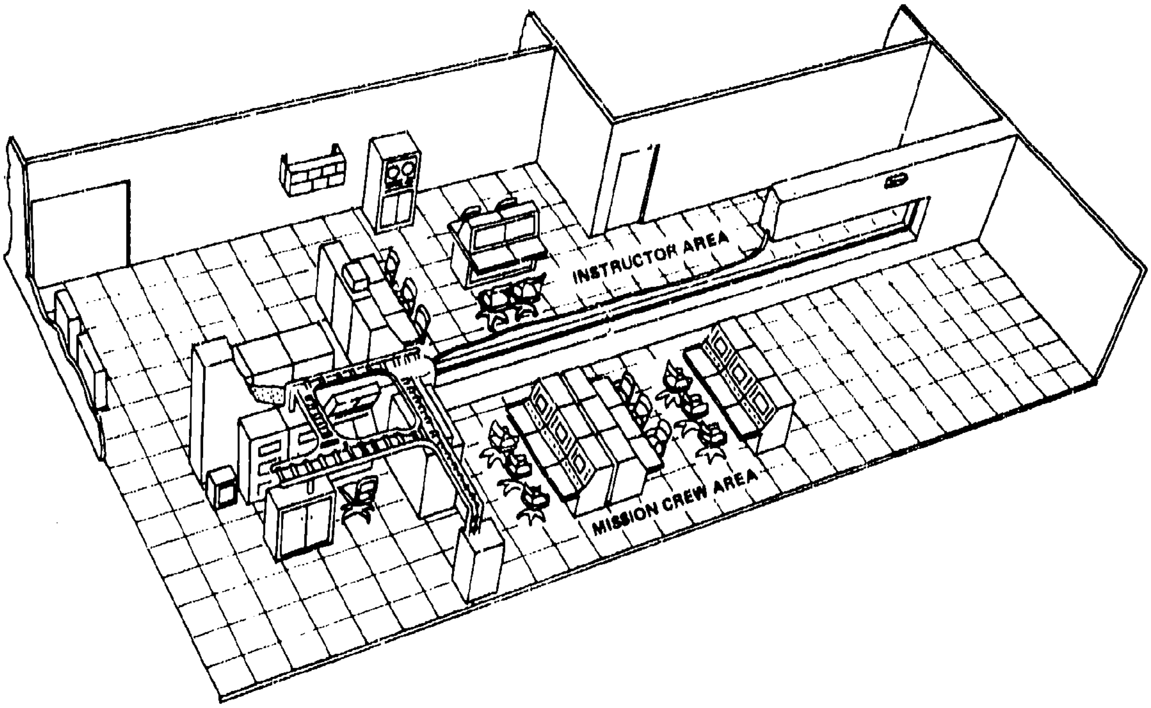


Figure 11. Layout of E-3A Mission Simulator Facility

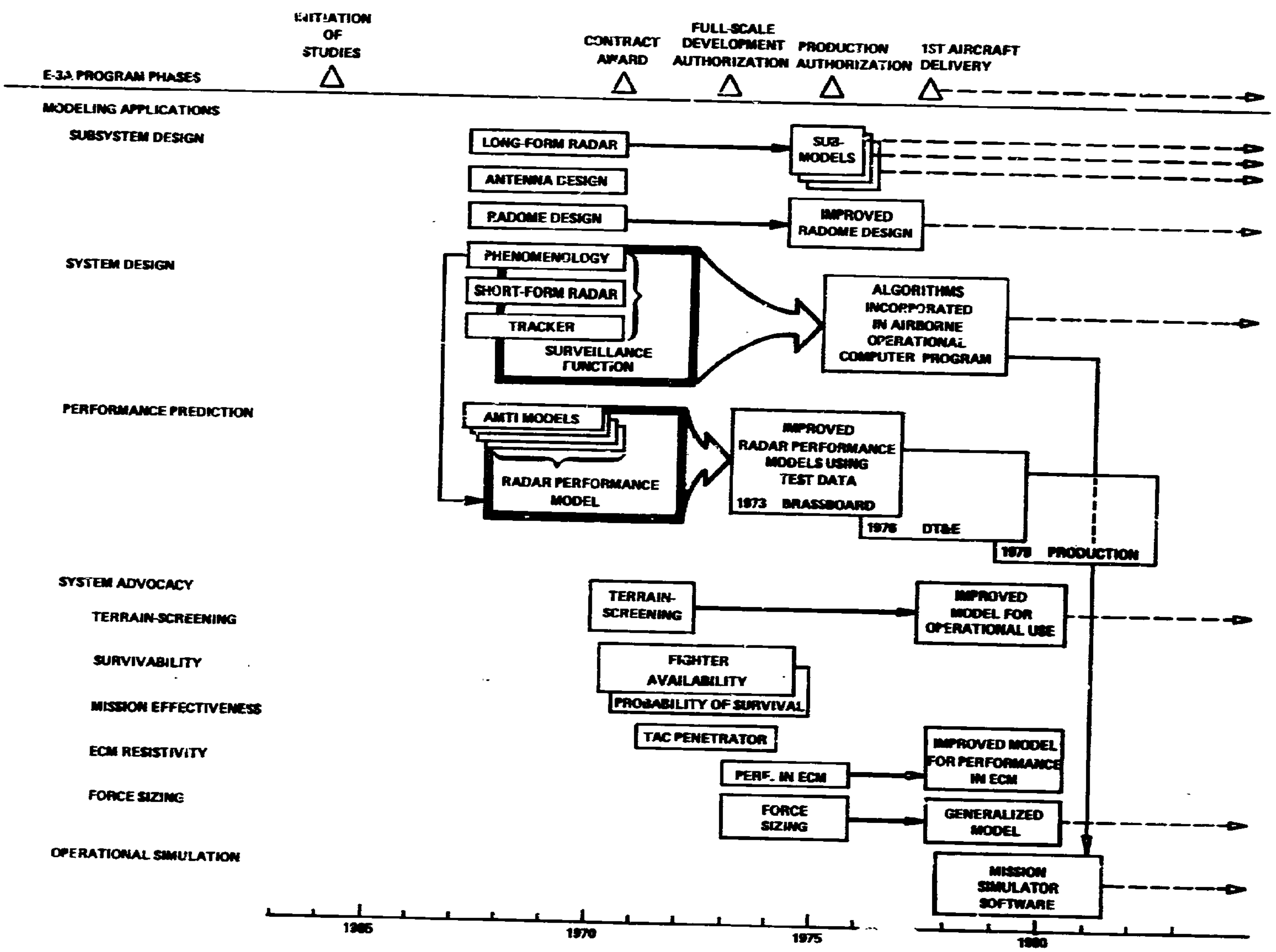


Figure 12. Summary of Modeling and Simulation During E-3A Program

E-3A NAVIGATIONAL COMPUTER SYSTEM REAL-TIME ENVIRONMENTAL SIMULATOR

Richard D. Healy
The Analytic Sciences Corporation (TASC)
Reading, Massachusetts

Samuel Newman
Naval Air Development Center
Warminster, Pennsylvania

ABSTRACT

The Naval Air Development Center is developing a software life-cycle support facility for the E-3A Navigational Computer System (NCS). The heart of this facility is a real-time environmental simulator which is used to simulate both E-3A avionics and the operational environment so that software problems with the included AN/ARN-120 Omega Navigation Equipment (ONE) can be investigated and that the impact of software changes can be assessed by a simulated mission refly. The ONE contains a 16-bit embedded minicomputer.

The environmental simulator is a hybrid system hosted in two digital computers connected by a specially designed real-time digital data link. Real-time simulation software performs two distinct functions: provides computer-controlled analog and digital input data to the ONE and respond to ONE guidance outputs, and provides "truth-model" aircraft data which can be used as a precision navigation reference.

The paper presents preliminary experience related to the design and construction of the environmental simulator for the software life-cycle support facility, describes some of the practical problems encountered in developing the simulator, presents interim resolution and potential long-term solutions, and discusses current status. Particular emphasis is placed on describing procedures used for implementing the simulator development guidelines: maximum flexibility and minimum essential design.

1. INTRODUCTION

1.1 The E-3A Navigational Computer System Software Life-Cycle Support Facility

The E-3A Navigational Computer System (NCS) is an integrated multisensor navigation system consisting of dual Delco AN/ASN-119 Inertial Navigation Equipments (INE), a Ryan AN/APN-213 Doppler Velocity Sensor (DVS), and a Northrop AN/ARN-120 Omega Navigation Equipment (ONE). Three embedded computers are used in the NCS: two inertial computers (one per INE) and an Omega computer in the ONE. System integration is performed in the ONE using a 24-state Kalman filter. A functional flow diagram of the NCS is shown in Fig. 1 (Northrop, 1975).

The primary purpose of the Software Life-Cycle Support Facility (LCSF) is to provide support to the U.S. Air Force in maintaining the operational ONE program. (Support of the operational INE programs is not a responsibility of the NCS Software LCSF.) The software maintenance task involves developing the capability to detect errors in the operational software, to change the software and test the changes, and to produce field-installable versions of the software. These capabilities represent the design goals for the NCS Software LCSF.

The NCS Software LCSF consists of two separate facilities: a Program Generation Facility (PGF) and an Environmental Simulation Facility (ESF). The PGF will be used to modify source code and assemble new program versions. The ESF will be used to test the software in a dynamic environment similar to that encountered in an E-3A. The power and flexibility of the ESF is derived from the real-time environmental simulator (ES): a hybrid system hosted in two digital computers connected by a specially designed real-time digital data link.

1.2 Relationship of the LCSF to Air Force Requirements

The E-3A system development is managed for the United States Air Force by the E-3A System Program Office (SPO), Electronic Systems Division, Air Force Systems Command. The user is Air Force Tactical Air Command (TAC), and maintenance responsibility ultimately rests with Air Force Logistics Command (AFLC). As part of its development mission, the E-3A SPO entered into an agreement with the Naval Air Development Center (NADC) to design and build a software LCSF for the E-3A NCS.

Development of the LCSF began in 1976. Since the beginning of the development, the design and development of the LCSF has been reviewed by E-3A SPO, TAC and AFLC representatives. Current plans call for NADC to assist in the transition of the LCSF to AFLC by 1984.

1.3 Organization of the Paper

This paper is organized into four sections. Section 1 presents an overview of the LCSF and its relationship to Air Force requirements. Section 2 discusses the principal goals of the LCSF, its hardware organization, and the software organization of the environmental simulator. Section 3 describes the development of the facility (with primary emphasis on the simulator) and discusses problems encountered, their solution, and lessons learned. Section 4 contains a brief summary of the development and describes the current status of the LCSF.

2. SOFTWARE LIFE-CYCLE SUPPORT FACILITY

2.1 Objectives

The E-3A NCS Software LCSF is designed to provide the software engineer with the capability to perform specific software maintenance tasks. From this perspective, six facility functions have been identified:

- Problem Report Evaluation - determine from a system deficiency report whether a specific problem has a software remedy
- Algorithm Modification and Program Generation - make a specific change to an algorithm in the ONE software, change the code, and produce a new program version
- Software Change Verification - test the change to ensure it meets specification and provide capability to debug new software
- Baseline Verification - perform automated testing to ensure old capabilities are not lost and new errors have not been generated
- Change Tape Production - produce a field installable version of the new program
- Configuration Control and Documentation - provide rigid control of user and LCSF software.

The environmental simulator plays an important role in problem report evaluation and software change verification, and it is the primary tool for baseline verification. The relationship of these steps to the overall system problem resolution sequence is depicted by the shaded areas in Fig. 2.

2.2 Hardware Organization

The LCSF uses two computers in addition to the ONE computer: a Hewlett-Packard HP-2113 is used as an interface processor and a Control Data Corporation CDC 6600 which hosts the simulation software. The HP-2113 controls all data flow within the LCSF and handles seven interfaces: two simulated INE interfaces, the control for the Canadian Marconi Company Omega signal simulator (which simulates the radio frequency Omega signal), a simulated DVS interface, the instrumentation (telemetry port) interface to the ONE, the data link to the CDC 6600, and the operator interface (through peripherals). All of the simulation software executes on the CDC 6600.

The LCSF has the necessary hardware to add a real INE for interface and data transfer testing with the ONE. (Mission refly cannot be accomplished with the real INE, because it is not possible to reproduce anything but a one-g static field in the laboratory.) Additional peripherals provide the capability to generate field-installable programs on cassette tapes and communicate with a remote International Business Machines IBM 370 computer which hosts the ONE assembler. The hardware configuration of the LCSF is summarized in Fig. 3.

2.3 Software Organization

The real-time simulation software resides in the CDC 6600 computer and can be divided into five functional categories

- Simulation Control
- Trajectory Generator
- Inertial Navigation Model
- Omega Signal Model
- Doppler Model.

The data flow between these modules is depicted in Fig. 4.

Because of the architecture of the host computer, the simulation control function includes both normal simulation executive functions and input/output functions. It synchronizes the simulator software with the 200 msec cycle of the interface processor, schedules simulation events and invokes necessary modules to complete the 10-sec major simulation cycle. Simulation control also handles the data transfer to/ from the interface processor at a 200 msec rate.

The trajectory generator (Berry, P.W., 1979) provides all-latitude simulation of the E-3A aircraft and includes a guidance function to handle simulated pilot steering, waypoint steering normally accomplished by the ONE-selected preferred INE, and pattern steering in response to ONE steering commands. It contains earth and gravity models and computes a specific force profile for use in the inertial navigation model. The trajectory generator provides truth-model navigation data for evaluating ONE performance.

The inertial navigation model simulates the navigation and alignment functions of the INE and functions in three modes: ground alignment, inflight alignment and navigate. To save simulation time, the ground alignment mode may execute an accelerated alignment sequence. Two distinct INEs are modeled in the inertial navigation model.

The Omega signal model supplies amplitude and phase data for eight Omega transmitting stations on the three primary frequencies (10.2 kHz, 11.33 kHz and 13.6 kHz) which correspond to the simulated aircraft position. Atmospheric noise data is also supplied in this model, and Omega anomalies (phase and amplitude biases, and solar flare-induced Sudden Ionospheric Disturbances and Polar Cap Anomalies) are modeled. To save development effort, the propagation portion of the phase model is a version of the U.S. Coast Guard propagation model, PROP2 (Morris, P.B., 1974), and the amplitude model is derived from an Air Force VLF amplitude program, POWERFLUX (Lewis, E.A., 1975). Both programs were modified to execute in real time.

The doppler model simulates DVS inputs to the ONE and operates in two modes: over-land and over-water. It transforms trajectory generator data to the proper coordinate frame.

The simulation software is summarized in Table 1 according to these functional divisions. The table lists approximate program size in lines of source code, describes the major characteristics of algorithm development, and summarizes additional software characteristics. (Program size data do not include storage requirements for large data arrays.)

3. FACILITY DEVELOPMENT

3.1 Development Approach

Development of the LCSF is a team effort. The Navigation Systems Design Branch, Communication Navigation Technology Directorate, NADC has overall responsibility for the LCSF and acts as both system engineer and development engineer for interface processor applications. The Systems Simulation Department, Systems Directorate, NADC serves as simulation consultant and is responsible for developing the simulation software. TASC serves as technical consultant on the E-3A NCS and on LCSF usage: TASC also designed the models for the ES. Computer Sciences Corporation is developing software for the interface processor.

Design of the ES software emphasized maximum use of existing software with minimal new development effort. As indicated in Table 1, approximately 40% of the simulation software is a modification of existing software. (This includes the relatively high risk models for Omega signal amplitude and diurnal phase shifts.) These modifications were designed to provide equivalent data in useable format in real time, and the original software provided excellent verification tests for the modified code.

TABLE 1
SUMMARY OF SIMULATION SOFTWARE

T-1920

MODULE FUNCTION	PROGRAM SIZE (LINES OF SOURCE CODE)	ALGORITHM CHARACTERISTICS	SOFTWARE CHARACTERISTICS
Simulation Control	4200	New Design	Approx. 2300 Lines HOL* and 1900 Lines of Assembler for Interface Processing
Trajectory Generator	1300	Moderate Modification to Proven Design	Modular; All HOL
Omega Signal Models	3700	Minor Modifications to Existing Design	Five Major Submodules; All HOL; Excellent Tests Available
Inertial	2200	New Design	Four Major Submodules; All HOL
Utilities	600	——	Includes Data Formatting; Mostly HOL
Doppler Model	300	New Design	Two Major Submodules; All HOL
TOTAL	12,300	Team Development Effort	Mostly HOL; High Degree of Modularity; Executes in Real Time

*HOL = High Order Language (CDC Fortran)

3.2 Problems, Solutions, and Lessons Learned

Numerous minor problems arose during the design and initial development of the LCSF, and additional "opportunities to excel" are anticipated. Four specific problem areas and their solutions are described below.

The most serious problem faced by the Air Force was scheduling. The decision to construct a software LCSF was reached after the software was provisionally accepted by the Air Force and while initial deliveries of the E-3A were being made to the user. Therefore, the LCSF was "late" the day the decision to build it was made. The solution to this problem was to construct two ES facilities: the final version described above and an interim facility with limited simulation capability that could be ready sooner. The interim simulation facility uses all of the interfaces needed for the final facility, is hosted only by the interface processor, and, therefore, can be used to perform most of the systems integration testing before all of the final simulation software has been coded and tested.

Documentation of the hardware interfaces to the ONE is less than adequate for the design task faced by NADC. In particular, design decisions and supporting rationale and motivations were missing from the package delivered to the Air Force. The problem is not that the equipment contractors did not fulfill their responsibility in the context of developing the E-3A NCS -- they did; rather, the problem is the changing scope and purpose to which the contractual deliverables were applied. Only partial solutions have been found, and the interfaces still represent a risk item in facility development. The lesson learned from this experience is that all interfaces to embedded computers must be thoroughly documented and understood at the time of hardware/software acceptance if the software maintenance task is to be accomplished by an external agency.

Two pieces of limited production Special Test Equipment (STE) were used by the equipment manufacturer in developing and testing the E-3A NCS. This equipment was not purchased by the Air Force to support the NCS during its life-cycle. Instead, special interface cards have been designed for the interface processor to provide visibility into the ONE software and eliminate the need for this equipment.

The device used to load the ONE program in the field was supplied as Government Furnished Equipment (GFE) to the prime contractor. As such, a single, largely undocumented procedure for generating cassettes containing the load module of the operational program using the STE was the only method available when this effort began. The problem was to eliminate the requirement for the STE and provide a more efficient procedure for generating change tapes. A solution was achieved in close cooperation with the equipment prime contractor, but substantial manpower resources were committed to the problem before a solution was achieved. The lesson learned from this experience is that the prime contractor must be made responsible (and compensated) for ensuring that adequate documentation exists for all software and equipment necessary to produce new program versions even if GFE is involved.

Although these problems were encountered, development of the LCSF is proceeding according to schedule and will contribute to successful accomplishment of the Air Force support mission for E-3A. It is anticipated that the first NADC-generated software change to the NCS program will be fielded in 1980.

4 SUMMARY

The E-3A NCS Software LCSF is being constructed at NADC to support the ONE software. Part of the LCSF is an environmental simulator: a hybrid system hosted in two digital computers connected by a specially designed real-time digital data link. Simulation software is used to generate a realistic, all-latitude aircraft trajectory generator, models for two INEs which simulate three operational modes (ground alignment, inflight alignment, and navigate), a doppler radar model, and models for calculating Omega signal amplitude, noise, phase and propagation effects under nominal and disturbed propagation conditions.

To meet scheduling requirements, the LCSF will be constructed in two stages. The first stage, an interim simulator, will be completed in December 1979, and will provide the capability to test the ONE software as well as exercise all of the facility hardware interfaces. The final configuration is scheduled for completion in July 1980.

The Air Force/Navy interservice arrangement for constructing the LCSF has been very productive in providing the expertise and tools necessary to build the facility according to the tight schedule. It is anticipated that the capabilities designed into the facility will provide a cost effective procedure for producing and testing new software for the ONE. Applying analytical insights about ONE operations to the task of designing the LCSF has already demonstrated cost savings in the design of the simulation software, and it is expected that the benefits will become more apparent when the LCSF becomes fully operational.

5. ACKNOWLEDGEMENTS

The authors acknowledge the assistance of Messrs. R. Cariola, A. Feznak, and J. Weiss from NADC and of Dr. N. Acharya and Mr. P. Berry of TASC for help in preparing the material for this presentation. Overall responsibility for coordinating the development of the LCSF in conjunction with Air Force requirements rests with Mr. F.K. Gardner of the E-3A SPO, who has been very helpful in dealing with procedural problems. The efforts of Mr. Healy at TASC have been partially supported by Contract No. N62269-79-C-0020 with NADC.

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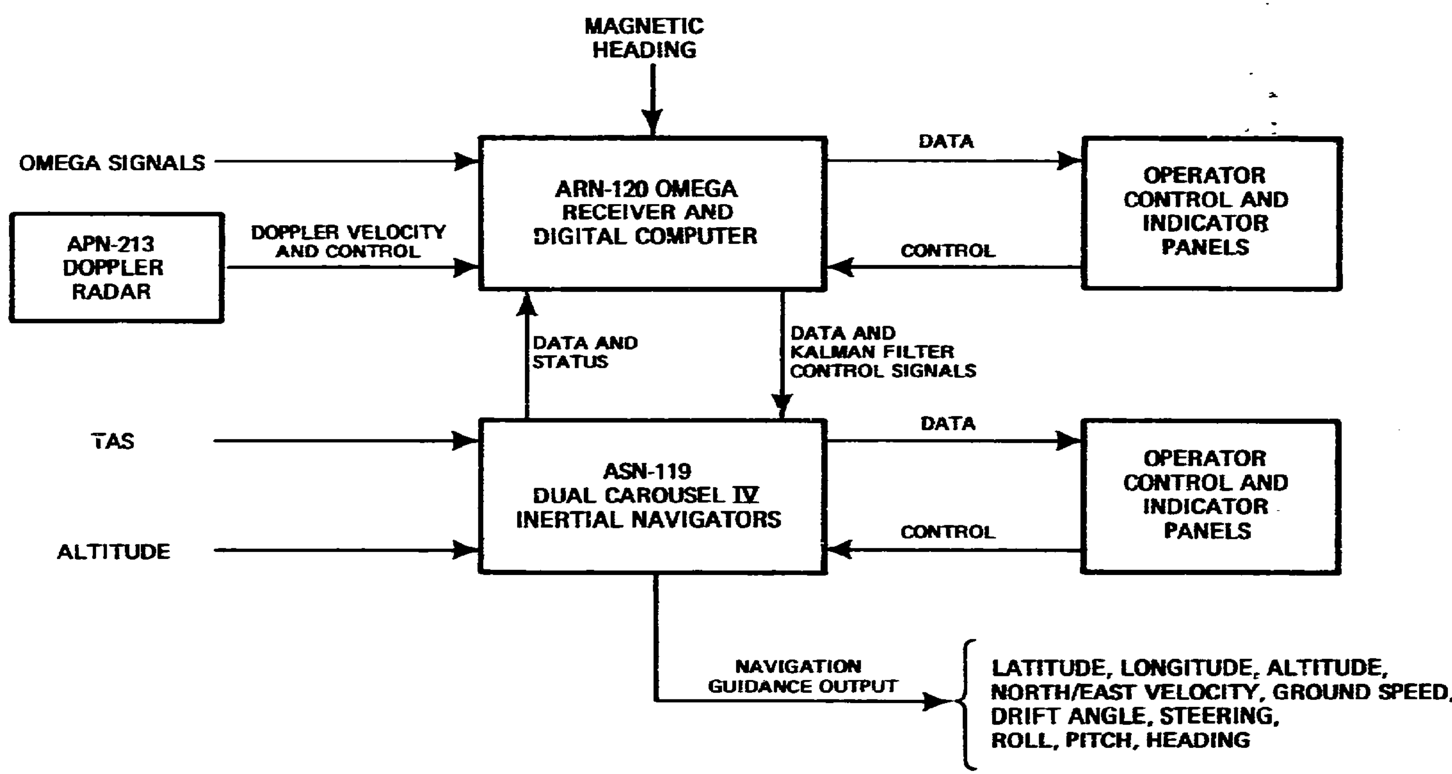

Figure 1 NCS Functional Flow Diagram

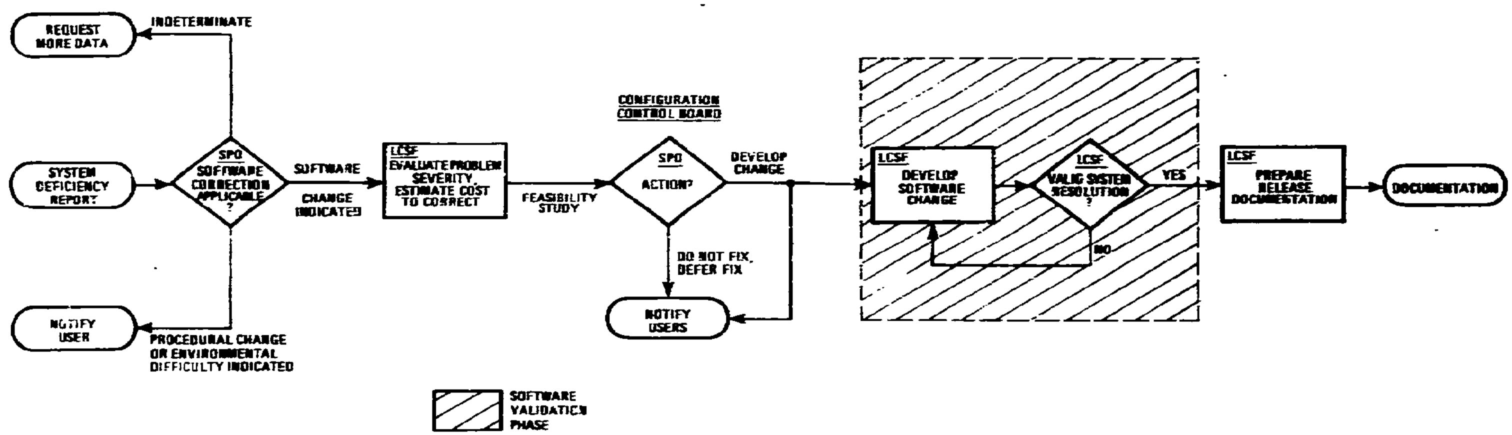

Figure 2 System Problem Resolution Sequence

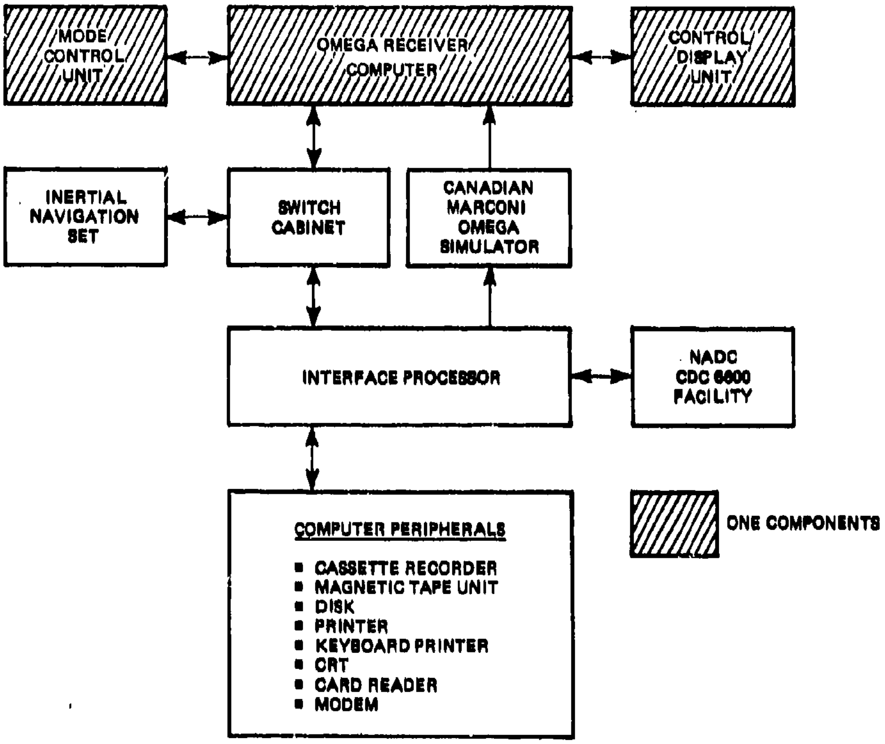

Figure 3 Hardware Configuration for the Software LCSF

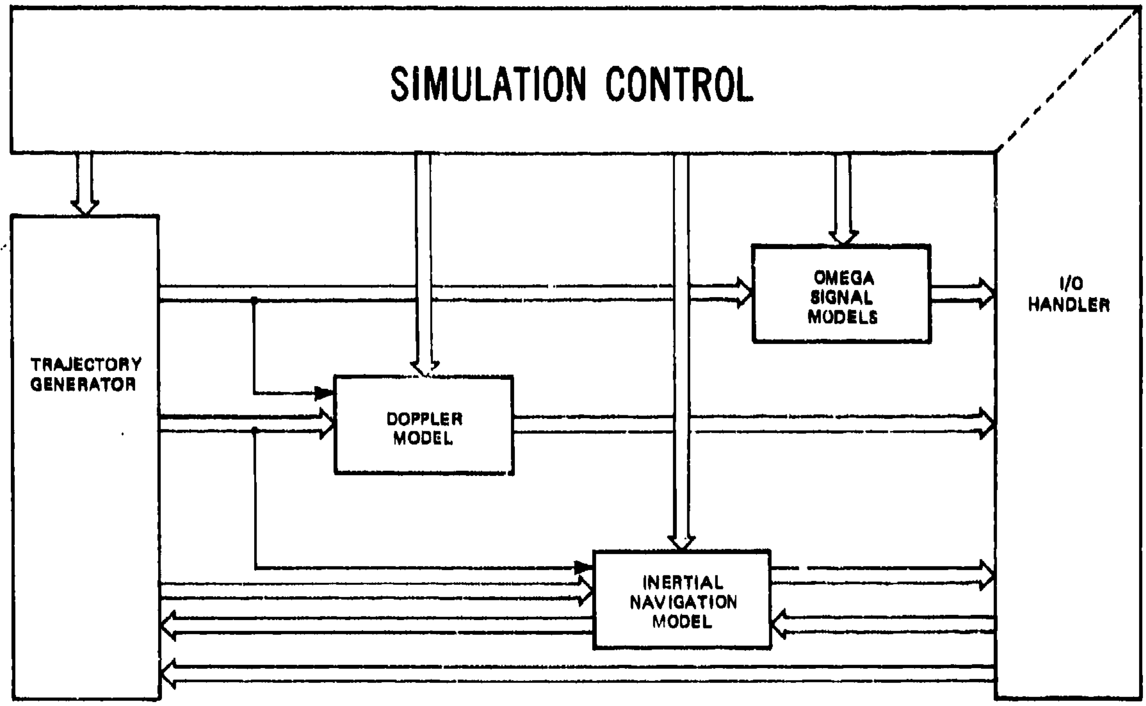

Figure 4 Data Flow in the Environmental Simulator

A JTIDS PERFORMANCE MODEL FOR THE E-3A

James G. Taylor
Boeing Aerospace Company
Seattle, Washington, USA

SUMMARY

This paper describes the communications link performance model developed to predict performance of JTIDS (Joint Tactical Information Distribution System) links between the E-3A and other aircraft and ground stations. The JTIDS is a time division multiple access system operating in the radio frequency band 962 to 1213 MHz and employs spread spectrum techniques.

The model is unique as it includes the performance effects on the JTIDS wideband frequency hopping receiver due to both the E-3A dual antenna system and specular and diffuse multipath signals.

Laboratory tests were conducted which provided receiver performance data for signals routed through dual antenna and multipath simulators. This simulator approach was also used in similar tests conducted by SHAPE Technical Centre for NATO. The results were essentially identical in the two test programs.

A flight test program was conducted which validated the link performance model. This validated model has greatly reduced costly E-3A flight testing and has provided predictions of JTIDS performance over a variety of communication link scenarios and flight conditions.

1. INTRODUCTION

This paper describes the communication link performance model that was developed and used during the USAF sponsored program that integrated the JTIDS (Joint Tactical Information Distribution System) Class I terminal into the E-3A (AWACS) aircraft. The JTIDS is a time division multiple access communication system, which operates within the radio frequency band 962 to 1213 MHz and employs spread spectrum techniques, i.e., pseudo-random bit-encoding within each information pulse and pulse-to-pulse frequency hopping. The JTIDS as installed in the E-3A utilizes a dual antenna system, one antenna in the nose radome directed forward, the other in a tail cone radome directed aft. The two antennas are separated by a nominal 126 wavelengths and therefore produce interferometer lobes at bearing sectors nominally centered at 90° and 270°.

A communications link performance prediction model was developed to predict JTIDS link performance between the E-3A and other air and ground terminals. This model was developed because of the necessity to provide link performance predictions for a multitude of link types, link geometries, aircraft headings, aircraft altitudes, terrain types and atmospheric fade situations. The alternative method was flight testing which would have been prohibitively expensive if all parameter combinations were tested.

The communications performance model is unique because it includes not only effects of the common link parameters such as transmitter power, receiver sensitivity, antenna gain, cable losses and atmospheric fade losses; but also performance effects on the JTIDS wideband frequency hopping receiver due to the dual antenna system and specular and diffuse multipath.

This performance model was validated by verifying that the performance predicted using the link performance model compared favorably with measured performance derived from flight test data collected during the E-3A flight test program.

2. E-3A JTIDS SYSTEM

JTIDS is a joint services tactical communications system. JTIDS terminals will be provided on the E-3A, and other military aircraft and ground stations. The first implementation of JTIDS was on the E-3A.

JTIDS users transmit and receive on a common channel. Thus, all users have access to the same information in real time. The JTIDS is nodeless; i.e., no communications center is required since all users transmit to all other users. Thus, loss of any one terminal or groups of terminals will not prohibit communication within the other surviving users.

The JTIDS basic time division is the time slot (duration 7.8125 ms): there are 128 time slots per second. The next higher level is a cycle which has a duration of 12 seconds or 1536 time slots. The highest level is an epoch which is 64 twelve second cycles or 12.8 minutes. Figure 1 provides a pictorial view of the time division architecture. A user can be assigned for transmission a minimum of one time slot per epoch and a maximum number depending on the transmit duty cycle limitations imposed by transmitter design and by electromagnetic compatibility considerations. The number of transmit time slots assigned to a user depends on the function of the user. In a single JTIDS net only one user can transmit during a single time slot. Multinet operation is also possible.

The JTIDS operates in the TACAN (Tactical Air Navigation) band, i.e., 962 to 1213 MHz. It is a spread spectrum system which utilizes pseudo-random bit encoding on each transmitted pulse and pseudo-random frequency hopping on a pulse to pulse basis. A message includes a synchronization preamble, four track refining symbols, and 109 symbols of data. A symbol consists of two 6.4 μsec pulses separated by 6.6 μsec and contains 5 channel bits.

2. E-3A JTIDS System (Continued)

Reed-Solomon forward error correction encoding is used to reduce transmission errors in each 225 information bit formatted message. The basic Reed-Solomon codeword is a (31, 15) codeword containing 31 five bit data symbols of which 15 are information symbols and 16 are parity symbols. Three of these blocks form the 225 bit message. The message header is a (16, 4) codeword (a shortened (31, 15) codeword) with four information symbols and 12 parity symbols.

The E-3A JTIDS uses a dual antenna system: one horn antenna is located above the weather radar in the forward radome and is directed forward. The other horn antenna is located in a tail cone and is directed aft. This antenna system was implemented to provide high and low elevation angle coverage and to provide optimum electromagnetic compatibility with other on-board systems. The two antennas are located approximately 126 wavelengths apart; hence an interferometer lobe region exists on both sides of the aircraft (Refer to Figure 2). The spacing between nulls of the interferometer lobes is approximately 0.4°. The antenna radiation pattern (Figure 2) was taken using an 1/7th scale model E-3A and depicts the gain profile at an elevation angle of 0°. The measurement was made at a scale RF of 7000 MHz. which is equivalent to 1000 MHz. This pattern is typical of the antenna radiation characteristics throughout the band.

3. LINK PERFORMANCE

The communication link performance prediction model defines link performance as a function of many communication system and propagation parameters. The measures of performance include message error rate (MER), range, link availability and link margin. Link availability is the probability that the message quality (MER averaged over an appropriate sample period) meets or exceeds an MER acceptable for the user (one percent for JTIDS). Link availability includes the normal statistical fluctuations due to atmospheric fading (Longley, A.G., 1968) and the effects of other fluctuations in received signal level caused by changes in range and variations in antenna gain. The latter are due to aircraft heading, altitude and attitude changes. Link margin is the difference between the received signal level and the signal level required to provide the desired MER.

The unique features of this model are the inclusion of the dual antenna system radiation pattern, effects of the dual antenna system on receiver performance and effects of specular and diffuse multipath reflections on receiver performance. This model also includes the usual communication link parameters; i.e., transmitter power, coaxial cable losses and receiver MER versus signal level characteristics. Atmospheric absorption and atmospheric fading loss aspects are based on a Boeing developed propagation model (Livingston, R. C., 1971) which is conceptually similar to the Longley-Rice (Longley, A. G., 1968) propagation model.

As discussed in paragraph 2., the antenna radiation pattern consists of major pattern lobes in the forward and aft regions and interferometer lobes in the broadside regions (Figure 2). Scale model azimuth radiation patterns were taken for elevation conics in three degree elevation angle increments from -15° to 15° relative to the aircraft centerline. Both maximum and minimum gain values were taken from the radiation pattern in two degree azimuth increments. The difference between the peak antenna and the minimum gain is the peak gain to null depth ratio (in dB).

The models which describe the effects of the dual antenna system and specular and diffuse multipath are discussed in paragraphs 3.1 and 3.2. The accuracy of the prediction model (excluding atmospheric fading and terrain multipath aspects) was validated by an extensive flight test program (paragraph 5.) Flight time was not available, however, to validate the terrain multipath model.

3.1 Dual Antenna Model

The antenna gain of the JTIDS dual antenna system cannot be determined at all azimuth angles in the conventional manner due to the effect of the antenna system on the performance of the receiver. As noted in paragraph 2., the antenna radiation pattern in the fore and aft azimuth sectors centered at 0° and 180° is similar to a conventional antenna pattern (no interferometer nulls) and the effective antenna gain is the peak gain of the radiation pattern at the particular azimuth angle.

However, the receiver interacts with the antenna interferometer lobes which occur at azimuth sectors nominally centered at 90° and 270°. Hence, a different antenna gain model was developed for the interferometer lobe regions. The receiver-antenna system interaction is described as follows. The azimuth angle of each interferometer null varies with changes in radio frequency (RF). When the incoming JTIDS signal direction of arrival (DOA) is within the interference null region, the antenna gain will vary from pulse-to-pulse as the RF hops in a pseudo-random manner throughout the JTIDS frequency band. Since the terminal utilizes Reed-Solomon error correction decoding and processes entire messages, the antenna gain will depend on the following: the signal DOA, the antenna gain variations with RF, the particular hop frequencies selected and the processing capability of the receiver.

The resulting antenna gain is larger than the minimum gain (the null depth) but less than the peak gain because of the receiver-dual antenna system interaction. In Figure 3, the peak antenna gain is reduced by a factor ΔS_1 (for peak gain-to-null depth ratio of 10 dB) due to this interaction. This reduction in antenna gain or receiver degradation in the presence of interferometer lobes is a function of azimuth angle and peak-to-null ratio and is determined by the laboratory measurements described in paragraph 4.1. These measurements provided data for MER versus signal level curves similar in nature to Figure 4.

3.1 Dual Antenna Model (Continued)

Figure 4 contains a reference curve which indicates the receiver performance at the peak antenna gain with no interferometer lobes. The other curves show receiver performance operating in an interferometer channel with peak-to-null ratios of 5 and 10 dB. The curves indicate that an increase in signal level above the reference level is required for the receiver to operate in an interferometer channel at the same MER. This increase in signal level in dB, e.g., ΔS_1 (10 dB peak-to-null ratio), is subtracted from the peak gain (dBi) to determine the effective antenna gain (dBi).

Many curves of the type presented in Figure 4 were generated from laboratory measurements (See Paragraph 4.1). Each curve was based on a combination of azimuth angle and peak-to-null depth as derived from the antenna radiation pattern data. The azimuth angle is an important parameter as it directly affects the time delay between signal arrival at each of the antennas.

At each azimuth angle in the interferometer region, the peak gain and peak-to-null ratio are taken from the antenna pattern and the time delay is calculated. The increase in receive signal (ΔS) required to operate in the interferometer channel is obtained from the MER vs signal level curve for each particular time delay and peak-to-null ratio. Then the effective antenna gain is the peak antenna gain minus the increase in receiver signal level, ΔS.

3.2 Multipath Model

The previous section described the model of the interaction between the dual antenna system and the receiver. This paragraph will discuss the E-3A JTIDS multipath model.

It is widely acknowledged that many narrowband communication systems are very susceptible to multipath degradation. An important performance feature of the wideband spread spectrum JTIDS receiver is that it inherently provides good performance in a multipath environment. To validate this premise, the JTIDS multipath performance was measured in the laboratory using JTIDS terminals and specially developed multipath simulators (see paragraph 4.2). These laboratory tests demonstrated that JTIDS has very good multipath performance.

The multipath model was developed by first predicting the multipath environment and then measuring JTIDS receiver performance in this simulated environment. The multipath environment consists of path delay and reflection attenuation as a function of aircraft altitudes, range, terrain type, terrain roughness and terrain electrical characteristics.

Differential path delay (hereafter referred to as path delay), i.e., time delay between the direct and reflected signals, is an important environmental parameter because the receiver multipath performance is sensitive to time delay. Path delay was related to aircraft altitudes and range by using well known geometrical relationships. Figure 5 presents the time delay between the direct and reflected signals as a function of altitude of one aircraft and range between that aircraft and the E-3A when the E-3A was at an altitude of 30,000 feet.

Reflection attenuation was determined as a function of aircraft altitudes, range between the aircraft, terrain type and terrain roughness through a specially developed computer program. The program considers the effects of the widebeam JTIDS antenna system as it illuminates the earth's surface and calculates both the specular and diffuse reflection components. These components were used to calculate the specular to diffuse power ratio and the total reflected power.

The reflected signal was judged to be entirely specular when the specular to diffuse power ratio exceeded 10 dB and entirely diffuse when the ratio was less than -10 dB. Specular and diffuse multipath were each simulated separately in the laboratory.

Figure 6 presents the reflected power attenuation for rolling hills as a function of one aircraft altitude and range between that aircraft and the E-3A when the E-3A was at an altitude of 30,000 feet. The rolling hills had average ground electrical properties and an rms height variation of 40 wavelengths. This very rough surface produces an almost totally diffuse reflected signal.

The values of multipath time delay and reflection attenuation used in the laboratory tests were based on those values in Figures 5 and 6 that were within the JTIDS E-3A communication range and altitude limits of the other aircraft.

The laboratory tests provided MER as a function of signal level for these values of time delay and reflection attenuation. An example of this multipath performance characteristic is plotted in Figure 7. Note that the signal level must be increased in a multipath environment in order to provide the same MER as achieved in a non-multipath environment.

Using the laboratory data, multipath losses at a message quality of one percent MER were determined as a function of time delay and reflection attenuation. This data was combined with the data in Figures 5 and 6 to produce multipath loss contours as a function of one aircraft altitude and range between that aircraft and the E-3A, when the E-3A was at an altitude of 30,000 feet. Figure 8 shows the multipath loss contours for rolling hills when the MER is one percent. The multipath loss contours in rolling hills do not include the attenuation effects of vegetation on the ground reflection signal. Hence, the contour values may be reduced if vegetation is present. Unfortunately, reliable models do not exist at 1000 MHz that allow prediction of that attenuation. Hence resulting JTIDS diffuse multipath degradation predictions tend to be conservative, i.e., are upper bounds.

4. LABORATORY SIMULATION

The techniques used to simulate the E-3A dual antenna system and multipath in order to determine their effects on the JTIDS receiver performance are discussed in the following paragraphs.

SHAPE Technical Centre (STC) conducted independent specular and diffuse multipath tests using the JTIDS terminal (Schemel, R., 1978). The STC multipath simulation was implemented in a different manner than the Boeing simulator. Both STC and Boeing used coaxial cables to provide the required time delay. The delay in the Boeing tests was provided at the JTIDS radio frequency. However, the STC test configuration translated the operating frequency to an intermediate frequency where the time delay was implemented and then up-converted back to the JTIDS operating frequency. The results of both STC and Boeing tests were comparable.

4.1 Dual Antenna System Simulation

The dual antenna system was simulated by splitting the signal into direct and delayed paths and recombining them prior to the receiver (Figure 9.). The direct signal simulates signal arrival at one antenna while signal arrival at the second antenna is delayed and reduced in amplitude relative to the first antenna depending on the signal DOA. Various time delays of the signal at the second antenna were achieved by using coaxial cables of different lengths. The peak-to-null ratio was adjusted by setting an attenuator in the delayed signal path. For example, if the attenuator were adjusted to provide equal loss in both direct and reflected paths, this would provide the situation where the gains of both antennas were equal (nominally, off the E-3A wings) and would result in a very large (theoretically infinite) peak gain to null depth ratio. The JTIDS frequency hopping will cause a random variation in the phase difference between the signals in the direct and delayed paths and results in interference nulling corresponding to the actual antenna system nulling.

Azimuth angle sectors were defined and the time delay corresponding to the sector midpoint was determined. Appropriate peak antenna gain to null depth ratios were determined for each angular sector from the measured radiation patterns of the antenna system mounted on a 1/7th scale model of the E-3A. Receiver performance degradation curves, i.e., MER versus signal level curves similar to Figure 4, were then measured for many combinations of time delay and peak gain to null depth ratios.

4.2 Multipath Simulation

As discussed in Section 3.2, both specular and diffuse multipath were simulated in the laboratory. The multipath simulation was similar in approach to the dual antenna simulation but covered a wider range of time delays. As indicated in Figure 5, the time delay can range from 0 nanoseconds to greater than one microsecond as a consequence of the possible ranges between the E-3A and another aircraft and the possible altitudes of that aircraft. Therefore, multipath time delays of 0, 100, 200, 300, 450 and 600 nanoseconds were used. The various time delays were simulated by using coaxial cables of appropriate lengths.

The reflection attenuation was provided by setting an attenuator located in the reflected signal path. The attenuator values were 0, 3, 6, 9 and 12 dB.

The specular multipath simulator included a direct path and single reflected path. Hence, the simulator configuration was the same as the dual antenna simulator (Figure 9) except for the different set of time delays.

Diffuse multipath reflection from the earth's surface can be characterized by a sum of many replicas of the same signal with different delays. The replica sum has a Rayleigh probability density for the signal magnitude and a uniformly distributed phase angle. To provide a model that is a reasonable approximation of these conditions, the signal is split into a direct and a delayed path. The delayed path is further divided into N paths with each path including a random phase shift device (Aranguren, W. L., 1973 and Schwartz, M., 1966). The N paths are then summed and delayed before passing through an attenuator. The signal statistics at the output of the attenuator will have a Rayleigh distributed envelope.

Rather than using random phase shifters, the basic signal properties of JTIDS were used to provide random phase. Properly chosen delay lines to provide operation over the JTIDS bandwidth were used which resulted in a uniform distribution of phase angles when the output of these delay lines was combined. The random phase for each fixed time delay was provided on a pulse to pulse basis as a consequence of the JTIDS frequency hopping. The use of six delay lines, i.e., N=6 paths, closely approximates the desired Rayleigh distribution. Time delays of 8, 10, 15, 19, 26 and 38 nanoseconds produce the same effect as if random phase shifters were used: i.e., six signals are provided which have statistically independent, uniformly distributed random phases. Figure 10 shows the multipath simulator used in the Boeing tests.

In developing the multipath simulator for the JTIDS terminal, it was important to evaluate the accuracy of the simulation and the tolerances required of certain components. The number of delayed paths used to simulate terrestrial multipath determines the accuracy of simulating the Rayleigh characteristics. Computer simulations of 2, 3, 4, 5 and 6 paths revealed that six paths were required to produce a good approximation to Rayleigh statistics. Figure 11 compares the magnitude of the six path simulator to the ideal Rayleigh distribution. A larger number of paths would produce an even more accurate simulator.

The tolerable variation of the simulator output due to different attenuations of the different lengths of cables used to simulate the various time delays was also examined. It was determined that variations in output level up to 6 dB did not materially degrade the accuracy of the Rayleigh simulation. Since the cable lengths were short and had attenuation differences less than 2 dB, the output variations were within 6 dB. Hence, the different cable attenuations did not affect the accuracy of simulating the Rayleigh distribution.

5. MODEL VALIDATION

The link performance model described in the preceding sections was validated by comparing link performance derived from flight test data with performance predicted using the link performance model. An E-3A flight test program was implemented which provided flight test data to determine link performance as a function of range and signal DOA. The flight profiles were designed to provide short range communication links in order to insure clear line-of-sight propagation paths and to minimize effects of atmospheric propagation anomalies. All flight profiles were designed to have straight line ground tracks and zero aircraft roll angles in order to enhance flight profile repeatability.

The flight test program used a JTIDS configured E-3A transmitting to a ground facility to collect air-to-ground performance data. Flight profiles were chosen to provide data when 1) the E-3A nose and tail were oriented toward the ground station and 2) the interferometer lobes in the broadside regions were oriented towards the ground station.

A small but important change was made to the JTIDS ground station configuration. An attenuator was inserted in the receive path prior to the first radio frequency amplifier. The attenuator was used to reduce the signal level at the receiver input to achieve message error rates at or near the specified level of one percent. The value of the attenuator setting is the link margin, i.e., the difference between the signal level at the receiver and the signal level required to provide the specified MER. Thus, the attenuator provided the means to determine the incoming signal level at the receiver. The use of receiver AGC or other conventional means to measure the received signal level are not practical for the wideband spread spectrum signals utilized in JTIDS.

The E-3A to ground link was the test link and had the attenuator in the receive path at the ground station. The ground to E-3A link was not attenuated and therefore was a reference link. The reference link was monitored to insure that the JTIDS terminals and the link were operating properly.

The flight test profile used to determine link margin and MER in the forward or aft direction of the E-3A is shown in Figure 12A. A straight line ground track was used; the aircraft either flew toward the ground station or away from the ground station. As the E-3A flew toward or away from the ground site, the attenuator was varied at the ground receiving terminal and the resulting MER monitored in real time. The goal was to provide an attenuator value that would result in a one percent MER at some range. The attenuator was first adjusted to produce an MER within a value of 0.4 to 0.8% or 2 to 10% if the aircraft flew away or toward the ground site. As the E-3A flew away from the ground site, the range increased which increased the propagation path loss. Since the attenuator setting was fixed, the increased loss caused the MER to increase to one percent or greater. Conversely, when the E-3A flew toward the ground station, the range and therefore the propagation loss decreased. As the attenuator setting was fixed, the reduction in path loss caused the MER to decrease to one percent or less.

This process was repeated several times during each pass. The most meaningful data was collected at ranges greater than 50 nmi as it was essential that the elevation angle of the E-3A relative to the ground station did not appreciably change during the measurement period in order to minimize changes in antenna gain. Changes in range were compensated during analysis of the data by adjusting the attenuator setting by the factor 20 log R/Ro where Ro is any convenient reference range. An example of a measured MER characteristic is plotted in Figure 13.

The flight profile used to obtain data on JTIDS performance for signal DOA within the interferometer region is presented in Figure 12B. As indicated, a straight line ground track was flown and the pilot attempted with good success to keep the roll angle at 0°. The above attenuator procedure could not be used for the broadside flight profile shown in Figure 12B, because the antenna gain changes rapidly with changes in azimuth angle. Hence, the following procedure was required. The attenuator setting was held constant throughout the entire round trip from position X to position Y and back to position X (Figure 12B). Then, three additional passes were made, each at different attenuator settings. MER was measured every 12 seconds, i.e., once every JTIDS cycle, throughout each pass. The data was then available as a function of attenuator setting, range and aircraft azimuth angle. The azimuth angular region over which the data was collected was divided into angular sectors of two degrees and the data allocated to the appropriate sector. For each angular sector, MER versus attenuation setting was plotted and the attenuation setting corresponding to a specified MER, e.g., one percent was determined. Generally, two to three data points were useful in an azimuth sector, because as expected, some of the MER's were either 0% or 100%.

For each 12 second JTIDS cycle, the following items were measured or calculated: MER, range, aircraft attitude, ground azimuth angle, aircraft depression and ground elevation angles. As part of the broadside data analysis, all ranges were normalized to 50 nmi and the attenuation values corrected accordingly. The MER versus attenuation data was examined to verify that it was monotonic, i.e., that the MER increased with increasing attenuation. Very little data was discarded for being non-monotonic.

The link margin for these flights was predicted using the communication link performance model. The predictions were based on the exact geometries and aircraft attitudes experienced during the flight tests. A link performance prediction was made for every 12 seconds of flight testing using actual geometrical and flight data, i.e., E-3A attitudes, range, altitudes, and position, that corresponded to each JTIDS 12 second cycle.

Finally, the predicted link margin was compared to the link margin derived from flight test data. This comparison was based on the evaluation of many independent measurements and indicated that the prediction model was conservative, i.e., the actual margin was generally greater than predicted (See Table 1). Hence, the model can be used to provide high confidence predictions of link performance for different links, altitudes, aircraft attitudes and geometries.

TABLE 1. COMPARISON OF PREDICTED AND MEASURED LINK MARGIN

E-3A ORIENTATION TO GROUND STATION	DIFFERENCE BETWEEN PREDICTED AND MEASURED LINK MARGIN IN dB
NOSE	-4
TAIL	+1
RIGHT SIDE	-4
LEFT SIDE	-5

6. CONCLUSION

A JTIDS communications link performance model for the E-3A has been described with emphasis placed on the unique capability for predicting performance of a wideband frequency hopping spread-spectrum transmitter/receiver operating with dual antennas in a specular and diffuse multipath channel. Laboratory measurements of JTIDS receiver performance in the presence of a simulated dual antenna and simulated multipath channel were conducted. This data was comparable with the data collected during independent STC testing. Descriptions of the dual antenna and multipath simulators were presented to assist other organizations in developing their own simulators.

The performance prediction model (excluding the multipath portion) was validated through collection of JTIDS E-3A to ground station link flight test data and comparing the measured link performance with predicted link performance. Details of the flight test program and test data analysis procedures were presented.

The method of using an attenuator to determine received signal level was presented. This technique is applicable to other communication systems where conventional received signal strength measurements cannot be made.

The validated JTIDS performance prediction model has provided predictions of JTIDS link performance over a variety of communication scenarios and flight conditions and therefore has eliminated the necessity for additional costly E-3A flight testing to determine communication performance.

ACKNOWLEDGEMENTS

The development, validation and application of the JTIDS performance model was the result of an E-3A program team effort at The Boeing Company. In particular, the author is indebted to George B. Rickey and the E-3A TDMA Design Group for laboratory, software development, computer processing and flight test support and Philippe J. deFaye and the E-3A Communication Technology Staff for analysis, model development and computer simulation support.

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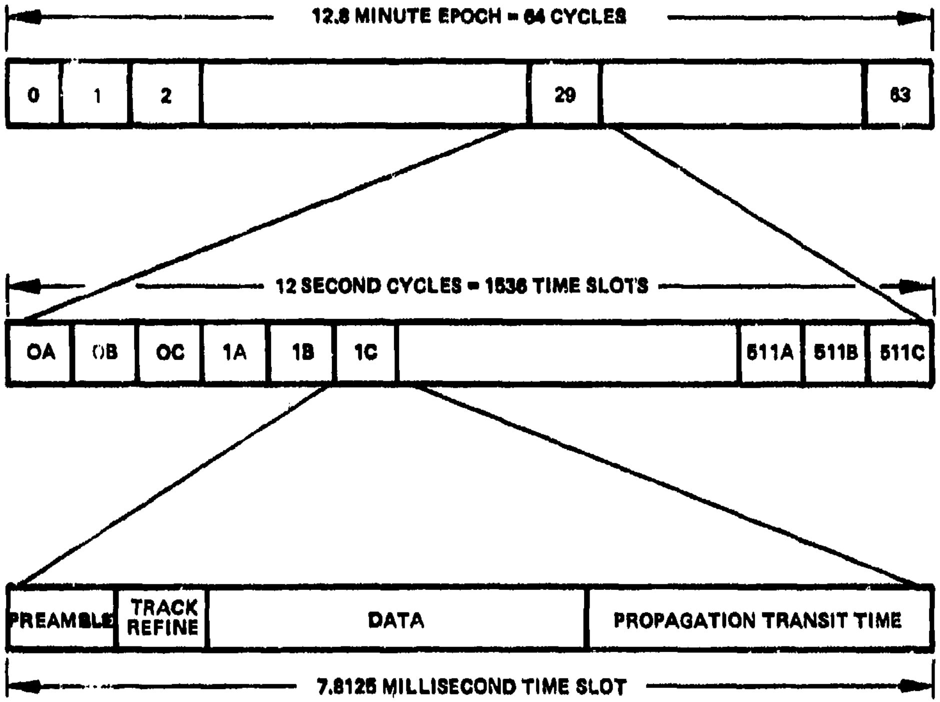


Fig.1 JTIDS timing architecture

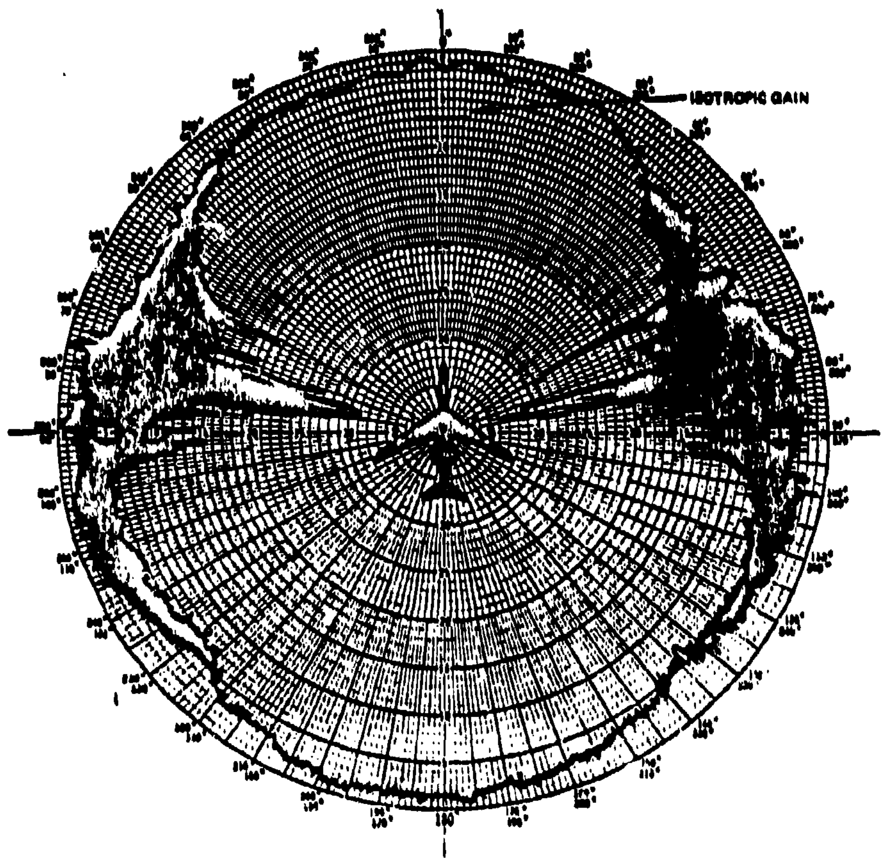


Fig.2 E-3A JTIDS dual antenna radiation pattern

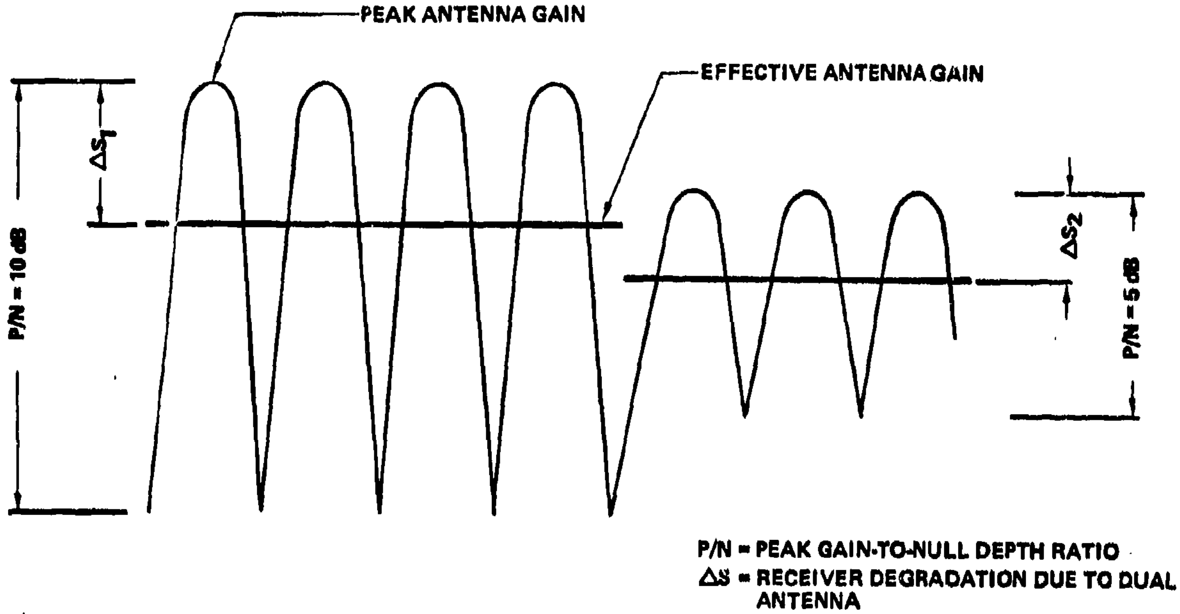


Fig.3 Example of effective antenna gain in the interferometer lobe regions

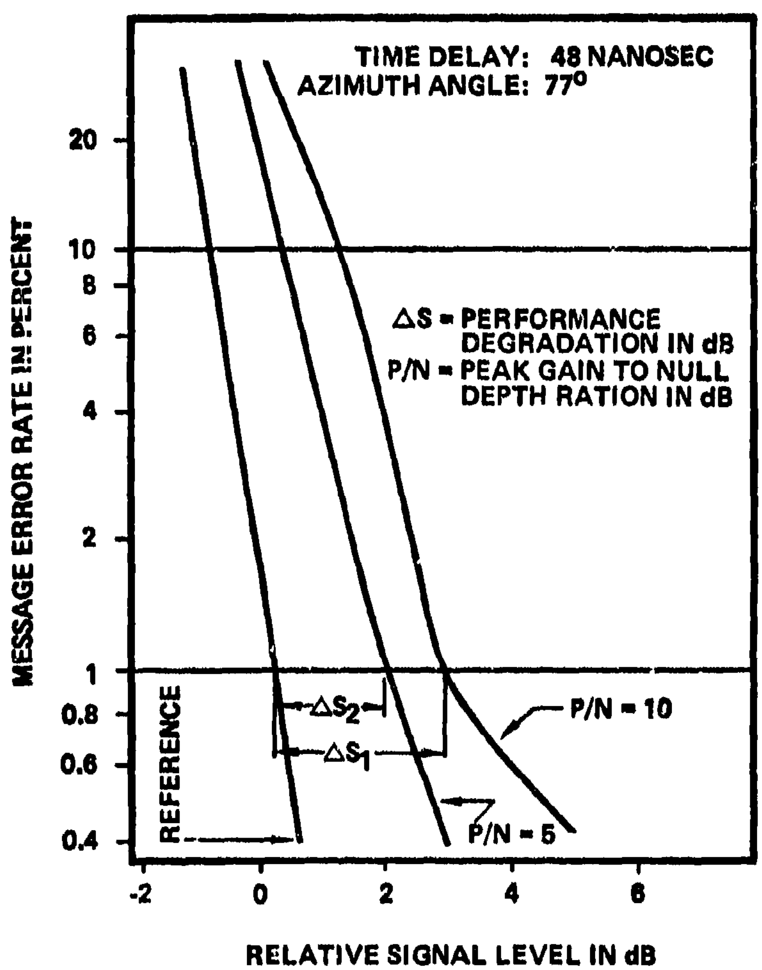


Fig.4 JTIDS receiver performance in the dual antenna channel

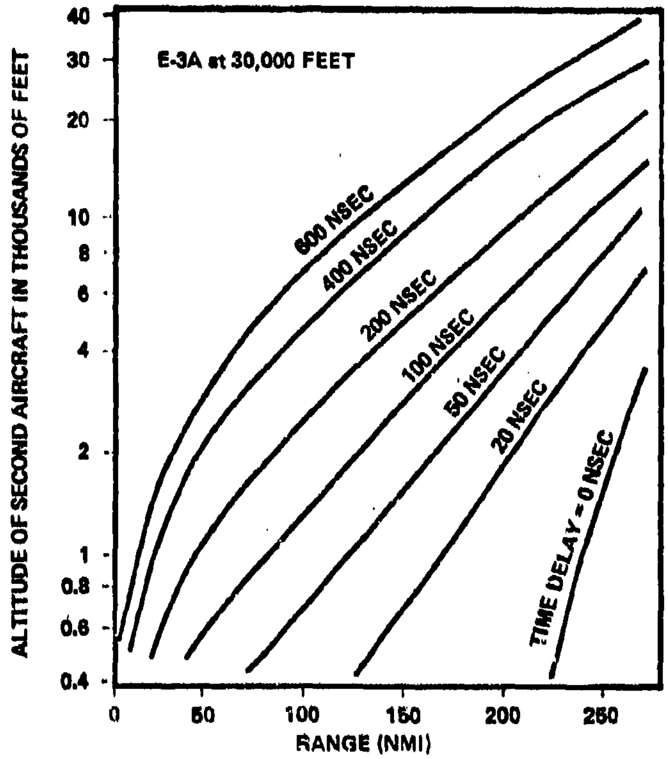


Fig.5 Relative time delay of reflected signal

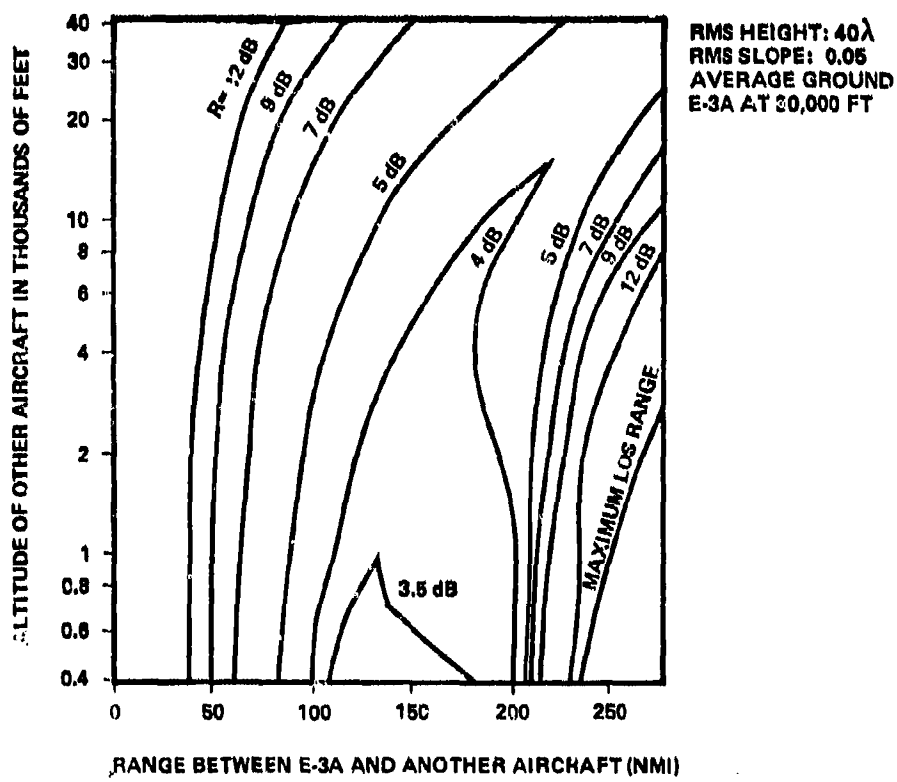


Fig.6 Reflected signal attenuation contours for rolling hills

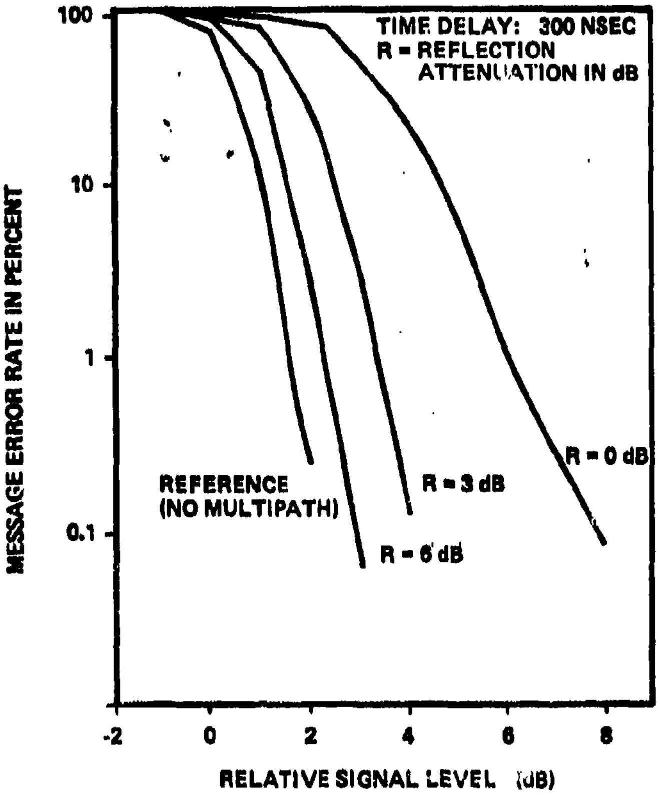


Fig.7 JTIDS receiver performance in a diffuse multipath channel

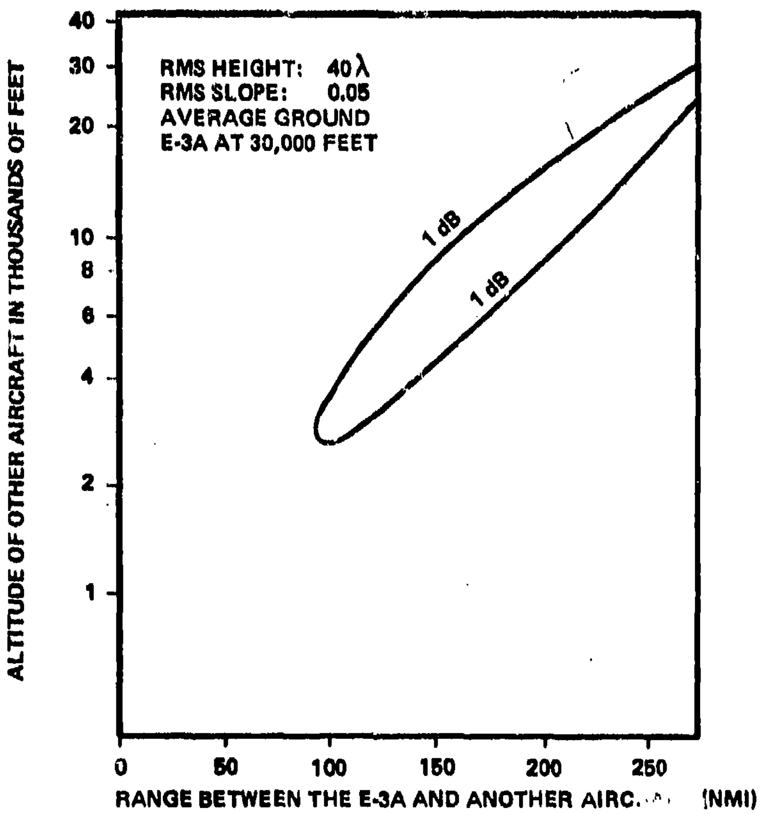


Fig.8 JTIDS multipath performance loss contours for rolling hills

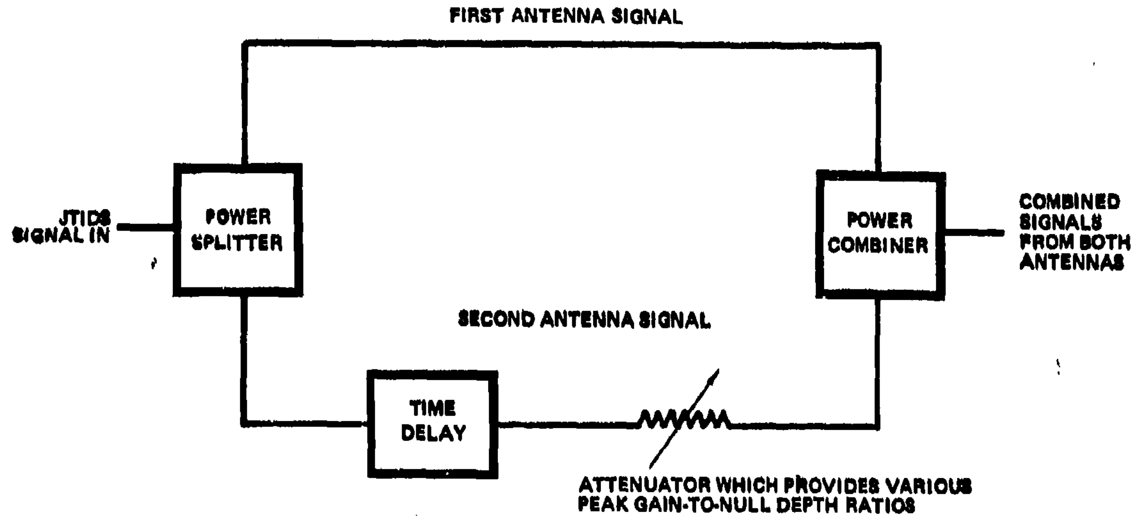


Fig.9 Dual antenna simulator

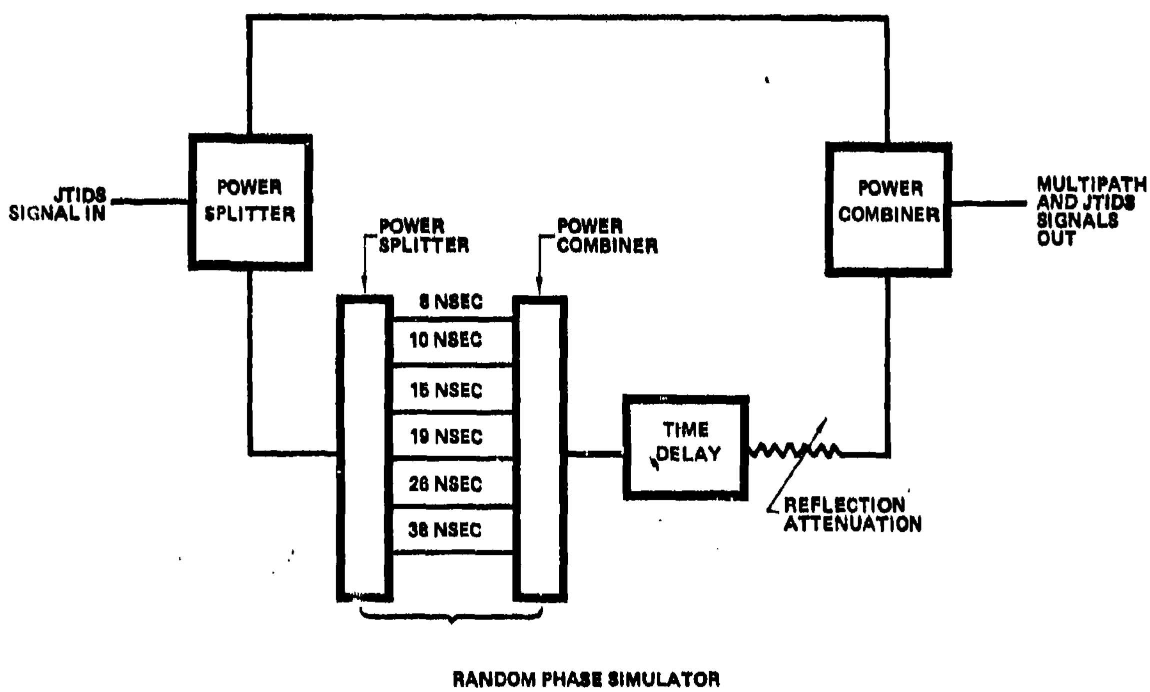


Fig.10 Terrain multipath simulator

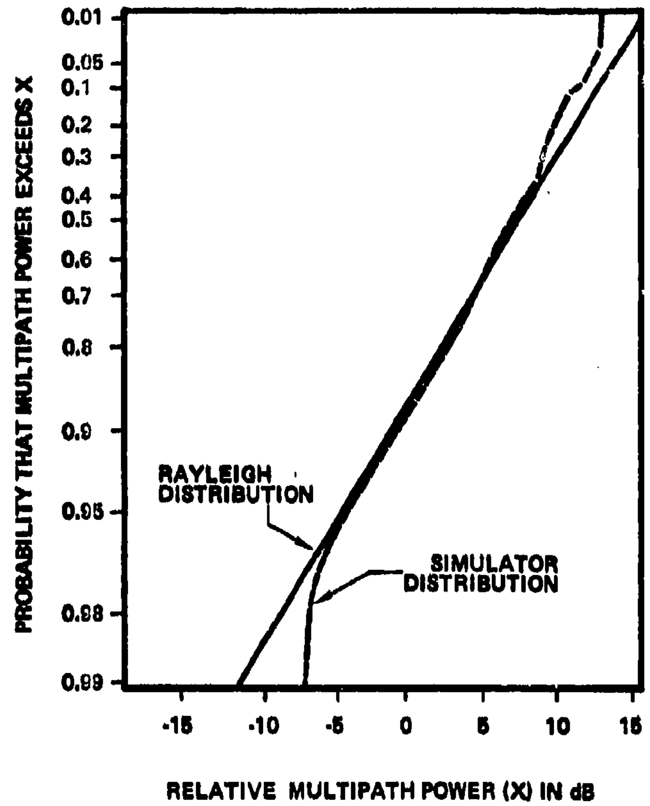


Fig.11 Comparison of six path simulator and Rayleigh amplitude distribution

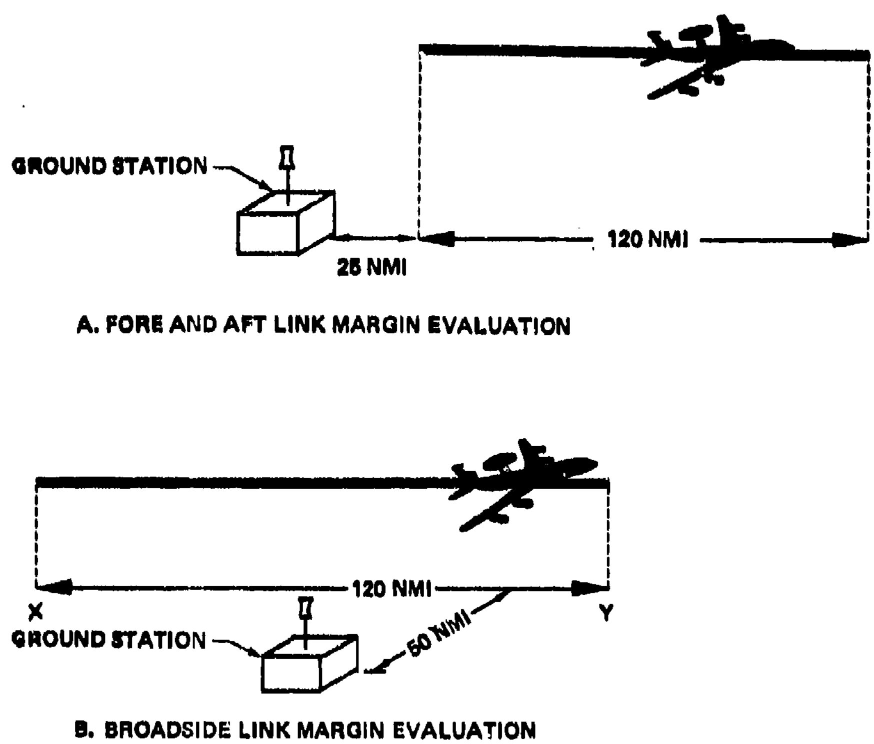


Fig.12 Flight test profiles

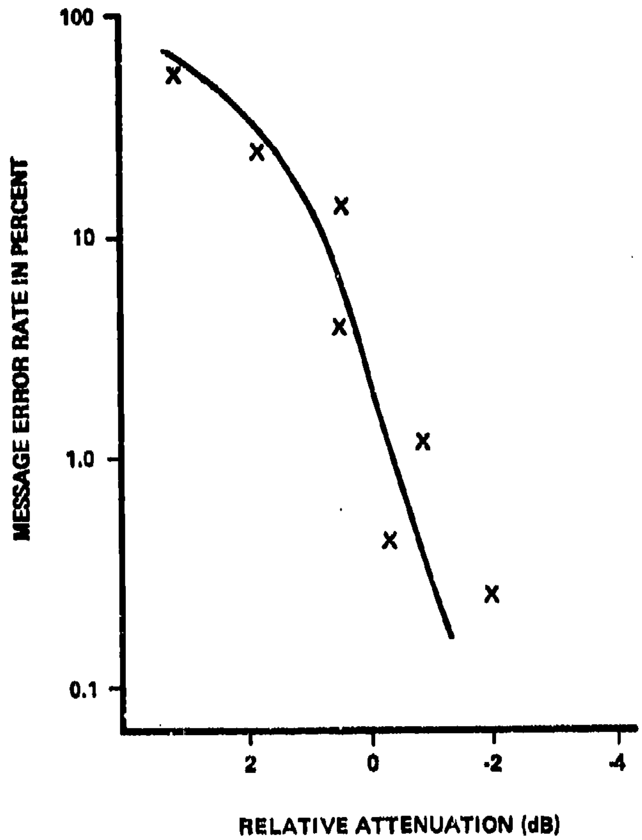


Fig.13 In-flight measured link margin

A MISSION TRAINING SIMULATOR FOR THE NIMROD MR MK 2 AND SOME ASPECTS OF THE DERIVATION AND VERIFICATION OF ITS SYSTEM MODELS

K. WELLS
SIMULATION GROUP MANAGER
Marconi Space and Defence Systems Limited, Hillend, Fife, Scotland

SUMMARY

This paper is divided into two separate and distinct sections. The first section outlines the function and facilities of a Mission Training Simulator for the Nimrod MR Mk. 2 aircraft and the second section relates to the derivation and verification of the system modules for such a Simulator.

1. A MISSION TRAINING SIMULATOR FOR THE NIMROD MR MK 2

1.1 GENERAL

The traditional roles of the fixed wing MR (Maritime Reconnaissance) aircraft are varied, i.e. maritime surveillance, ASW, search and rescue, etc. During these roles there are often periods of intense concentration required from the crew members during which complex and subjective data, from a variety of sensors, must be speedily and accurately interpreted and correlated so that the correct tactical decisions are made. In order to maintain a high level of concentration, both as an individual sensor operator and as a member of the crew, each crew man must be totally familiar with current target sensor information as well as current tactics. Intensive training must be directed towards this total crew capability - the Mission Training Simulator fulfils this role.

The initial requirement for the mission simulator was formulated in the mid sixties prior to the introduction into service of the Nimrod Mk. 1. Three Mk. 1 simulators subsequently entered service with the Royal Air Force in the early seventies.

Each simulator provides the capabilities for integrated crew training in all operational missions. These missions range from the basic to the most complex, and the crew may be trained in a complete mission covering the full range of operational roles applicable to the Nimrod. This capability is available for not only the ab initio trainee but also for the experienced operational crew in continuation training.

The simulator provides a high level of simulation of most environmental and target effects, the training being carried out under the control and surveillance of a team of instructors.

The simulator comprises a fuselage, the interior of which provides an accurate representation of the Nimrod Sensor and navigational area. Within this area, sensor, communications, navigation and tactical/weapons systems are reproduced. To achieve the proper psychological involvement from the trainees, there is no 'over the shoulder' instruction; instead, instruction is undertaken from an externally situated instructor console.

Currently, the simulators are undergoing a major avionics refit to reflect the changes in the RAF's Nimrod MR Mk. 2. This refit necessitates the modification to Mk. 2 standard of the two prime sensor systems; acoustics and radar. In addition, the navigation and central tactical systems are being updated. The modifications both to the acoustics and to the radar will be discussed in some detail in this paper.

The acoustics equipment consists of two identical sets; each set, comprising control, processing and display facilities, can process and display data from a wide range of sonobuoys either singly or in various mixes. System operation is based upon a digital computer sub-system in which is resident high level language implemented software. Each operator is provided with a CRT display, chart recorders and keyboard facilities for the control of processing operations. Data received at the system is synchronized with aircraft references before being gain-normalized, digitized and filtered. The data is then suitably formatted for conversion from the time domain to the frequency domain for display. At each operation, the operator has control over all processing parameters such as sampling rates, filtering bandwidth, magnification factors, integration time constants, and so on. Target data such as identification and tracking can be transferred to the central tactical system for correlation with other sensor data.

The radar is a high resolution, anti-submarine radar with a long range surveillance capability. Sea Clutter performance is achieved by the use of frequency, spacial and temporal characteristics of sea clutter and by the automatic creation of a threshold reference to the background clutter. The resulting decrease in false alarms presented on the radar display enables detection of small targets in high sea states without impairing long range performance against large targets. Processing is digital computer based allowing tracking and classification of detected targets. The processed video is scan converted and presented on a raster scan type display which gives the operator the choice of a number of display presentation modes, including standard PPI, B scope and high resolution A scope. Two secondary radars are integrated into the primary radar system, these being an IFF and an I-band interrogator. The coded replies received by the secondary radar are presented on the primary radar display.

Simulation is based upon the use of unmodified avionics systems including the associated operational flight software. Thus the acoustic simulation starts at the output of the receiver - all things 'external' to and including the receiver being simulated and all things 'inwards' being as aircraft. In a similar manner the radar simulation produces signals corresponding to the output of the FI detector of the dispersive unit.

The simulation involves the modelling of a large number of facilities associated with both the avionics systems and their operational environment. It can be summarised as the provision to the trainee operators of appropriate visual and audio stimuli, each of which reacts in real time in a realistic manner in accordance with the dynamically changing exercise scenario as initially specified and subsequently controlled by the instructors. These stimuli comprise target and environmental characteristics which are controlled by the instructors.

An outline of the functions of the Simulator for Nimrod MR Mk. 2 Acoustics and Radar is given in the following paragraphs.

1.2 ACOUSTICS SIMULATION

1.2.1 Target Simulation

Target signals contain information which allows the skilled operator to classify and locate his target of interest. These signals comprise broad band noise and sets of discrete frequencies. It is the characteristics of these signals which allow the operator to determine the classification of the target under surveillance.

Complementary to these target characteristics are other, usually more subjective, audio effects the presence, and in some cases the absence, of which aids classification. Typical of these effects are cavitation, engine and propeller associated noises. These audio characteristics reflect the appropriate changes of the simulated targets' manoeuvring parameters.

1.2.2 Environmental Simulation

The environmental models take into account audio propagation and environmental noise characteristics - different models are used depending upon the particular type of sonobuoy in use.

1.2.3 Sonobuoy Simulation

Target and audio signals are processed in accordance with the characteristics of the sonobuoy being monitored. The signals are modified to take into account specific sonobuoy characteristics such as hydrophone frequency response, beam forming capabilities and so on.

1.2.4 Receiver - Transmitter Simulation

This represents the final stage of the simulation chain and comprises the routeing of the incoming signals to the correct aircraft equipment channel and the modelling of effects related to RF transmission/propagation and reception.

1.3 RADAR SIMULATION

1.3.1 Target Simulation

Signals comprising video signals appropriate to the output of the radar IF detector in the dispersive unit are fed into the avionics system for presentation and display to the operator. Video returns are generated to represent a wide variety of target types including aircraft, helicopters, various surface vessels, submarines and oil rigs.

The generation of the correct target responses involves the calculation of the respective signal level taking into account system variables including transmitter power, antenna gain and polar diagrams, transmitter frequency, electromagnetic and weather attenuation and target scintillation. The target responses are appropriate to the operator display mode selection. Secondary target effects are associated with target-borne secondary radar IFF and I-band transponder replies. In the case of IFF, these coded video returns contain information which provides target status data. Additional target-related effects are simulated such as the effect on the radar of target-borne electronic counter measures.

1.3.2 Environmental Simulation

The effects on the radar of such environmental reflectors as land mass, cloud mass and sea clutter are included, the video corresponding to land and cloud returns being produced using flying spot scanner techniques. Thus it is necessary to take into account the variation of video returns with a large number of variables such as sea state, wind, transmission polarisation, aerial tilt and spacial, temporal and frequency correlation characteristics.

1.3.3 Receiver - Transmitter/Scanner Simulation

The operation of the primary scanner aerial, transmitter and receiver systems, and the secondary IFF transmitter/receiver and the I-band interrogator, are entirely simulated.

Operational characteristics of the transmitter/receiver and scanner aerial avionics units (e.g. transmitted power, polar diagrams, etc.) are implemented entirely by computer software and are utilised in the target and environmental program models. The primary radar scanner platform is simulated by means of a hardware electronic scanner which, under control of the Simulator computer, will produce the appropriate azimuth position indication required by the avionics radar processor.

2. DERIVATION AND VERIFICATION OF THE SYSTEM MODELS

2.1 GENERAL

Whereas the first part of this paper outlined the facilities of the Nimrod MR Mk. 2 which were required to be simulated and the methods which have been utilised to achieve this aim, the second part describes the general methodology adopted to derive the models required to meet the objectives. It defines the initial requirement of such models, relates realism with training objective, determines the need for flexibility as well as expandability and goes to some depth into the implementation and verification phases.

Throughout this paper the term 'model' is used to denote the total system, comprising both hardware and software, which is required to simulate the aircraft avionics systems in real time in accordance with a training scenario as specified and controlled by the Instructors.

2.2 DEFINITION OF REQUIREMENT

The first question to be answered is the apparently simple one of "what is it that we are trying to simulate?" If this question is asked of the eventual user, the answer is a simple one - an MR Mk. 2 Nimrod. This to him fully defines the requirement even though, at the time at which the question is asked, he has no clear understanding as to what an MR Mk. 2 Nimrod comprises since, of necessity, the question must be asked at a very early stage in the development of the aircraft systems. This simple statement of requirement must first of all be translated into an explicit and quantitative statement of that requirement. This involves not only a definition of the aircraft systems but also a definition of the training requirements.

The definition of the aircraft systems involves detailed engineering discussions with the prime system manufacturers. At this stage there is usually a fair amount of prime system requirement design data available. This data, however, is produced to define how the avionics systems are to perform in their airborne environment and is, by definition, a statement of design intent rather than design achievement. The two are sometimes at variance and it is often in the very areas of this variance that significant training requirement exists.

Training requirements are defined in conjunction with the RAF specialized training branches. With these organisations such questions as "how is the simulator to be used in it's training role?; what are the relative importances attached to the different aspects of the training requirements?; what is the role of the instructors and what controls do they require.; how many and what types of target must be simulated?", and so on, are discussed. This process is very much a two way dialogue involving cost effectiveness assessments.

During both these phases, additional support and information is obtained through discussions with the appropriate specialized government research establishments. These are the organisations which are directly involved with the development of the prime avionic systems and which are also concerned with the collection and analysis of 'targets of interest' characteristic data.

Defining the requirements is thus seen as a process of collecting a very large amount of data. Much of this data is irrelevant from a simulator point of view and it must all be very carefully analysed, filtered and condensed into a definitive statement of the requirement. This requirement, in the form of an operational requirement specification, is agreed with the end user.

2.3 MODEL CHARACTERISTICS

Having produced an operational requirement specification, the next step is to produce an engineering implementation specification. It is at this stage that the process of the derivation of the system models begins. Any model used must have specific characteristics which are directly related to the nature of the simulator. The required model characteristics are discussed below.

2.3.1 Realism

Great care is taken in the simulator to achieve, as far as is cost effective, a totally realistic environment for the trainees. This is necessary to induce the appropriate psychological involvement in order that effective training transfer can take place. However, this realism, like beauty, is only skin deep in that, provided it appears as the real aircraft to the human senses, it is good enough. This may

2.3.1 Realism

Great care is taken in the simulator to achieve, as far as is cost effective, a totally realistic environment for the trainees. This is necessary to induce the appropriate psychological involvement in order that effective training transfer can take place. However, this realism, like beauty, is only skin deep in that, provided it appears as the real aircraft to the human senses, it is good enough. This may simplify the modelling task in that a very high degree of sophistication in the model, such as might be required for predictive modelling, is not required. However, careful attention must be paid to the provision of such unwanted signals as noise and artifact since this is very often of significance from a training point of view.

2.3.2 Flexibility/Expandability

The requirement for a highly flexible and expandable model is a result of a number of factors. By its very nature the training simulator is one of the first items in the total aircraft development programme to be required in service and yet it is usually the last to be specified. The implementation timescales can be compressed only so much and simulation system complexities are now such that significant lead times are unavoidable. In these time frames it is inevitable that significant changes to the aircraft systems will take place. At the commencement of system modelling, it is therefore necessary to attempt to predict in which areas these changes are likely to take place and build in a flexibility to the corresponding model.

This is where the experience of both the simulator manufacturer and the prime equipment manufacturer, can be pooled to good effect.

The end user becomes more and more familiar with the aircraft systems, this being an inevitable learning process during the aircraft development phase. Thus, his initial tentative ideas at the commencement of the operational requirement specification may significantly change as a result of this learning process. This change will inevitably influence the simulation philosophy and consequently the modelling. A similar requirement for flexibility arises from the fact that all simulators after a relatively short in-service operation require a fairly extensive modification.

Many of the effects being simulated are of a very highly subjective nature, for example, it is very often difficult, if not impossible, to define in a quantitative manner such effects as target generated audio effects on acoustics and processed sea clutter effects on radar. These effects in the early stages can be defined only in a relatively broad manner. It is therefore important that, from the onset, the simulation is implemented in such a way that a large number of adjustable parameters are made available. In this way the system can be 'tuned' to match live trials data as it becomes available further downstream in the aircraft trials programme.

By their very nature there is often a significant training requirement for operating equipment in possibly rarely encountered environments. For example, it could be very important to train an operator to interpret essential information and take appropriate action when the system is performing against enemy transmitted counter measures. Inevitably, the exact performance of the equipment in such an environment is often ill defined - some high degree of prediction being required at the modelling stage. Thus a high degree of flexibility is required for subsequent adjustment of the system to match trials and operational data which may not become available until a long way into the simulator lifetime.

2.3.3 General Purpose

The fact that many of the target associated characteristics which are to be simulated are of a very highly classified nature, influences the model used. One of the prime functions of the acoustics system is target identification. This identification is based largely upon recognition of the frequency characteristics of the target emitted signals. By the subjective nature of these signals, proficiency in recognition requires continuous and repetitive exercising. Also, by their nature, these exact frequency contents are highly classified. To circumvent the requirement for a detailed knowledge of the exact frequencies, the simulation has to be capable of generating signals each characteristic (for example frequency, amplitude) of which is operable within broadly defined limits.

The user in-service specifies the detailed and specific parameters which define particular targets of interest. This allows him continuously to update his simulated targets throughout the operational life of the simulator and the aircraft. Effective training can consequently be carried out utilising fully up to date intelligence sources.

2.3.4 Real Time Operation

That the model must be operated in real time may restrict or even preclude the use of the models with which the prime systems have been developed for the aircraft. In conjunction with the expandability/flexibility requirement this very often dictates the hardware/software model partitioning. Thus, required signal data rates which would normally suggest the use of dedicated hardware may, in effect, need to be implemented by software in areas where a future high degree of changeability is anticipated.

2.3.5 Predictive

Little operational experience is available until the aircraft is fully operational and that is a long way downstream as far as the simulator development is concerned. At commencement of simulator design it is necessary to extrapolate from known characteristics, based on existing sensor performance, to possible future characteristics based upon predicted sensor performance. To illustrate this there is a wealth of target acoustics signature information available based upon existing sonobuoys and processing systems. New sonobuoys and processing systems in development improve the system parameters, thus there is an extension of the frequency band, and improvement in resolution and threshold values. It is necessary to try to predict how known target characteristics might be changed and also what new characteristics might become apparent as a result of the changed system parameters.

2.4 MODEL IMPLEMENTATION

The requirement, as expressed in terms of an operational specification and a set of model characteristics, must now be engineered. It is at this stage that such design considerations regarding the extent to which the avionics is to be modelled and the hardware/software partitioning are answered. As far as the former is concerned the answer is very largely dictated by the required implementation

programme. Thus the required in-service date of the simulator relative to the aircraft imposes a tight simulator development timescale. The degree of complexity of the avionics systems together with the fact that they are quite often subject to significant and rapid changes during the aircraft development programme, precludes any attempt at their direct simulation. Thus avionics are fitted rather than being simulated.

The exact extent to which the aircraft systems are fitted to the simulator and at which point in the aircraft signal processing chain the simulation, per se, starts, is decided largely on cost effectiveness grounds. Thus both the acoustics and radar simulations produce simulated signals corresponding to receiver outputs.

The hardware/software partitioning is arrived at, taking cost considerations into account, by a balance between system data rates and flexibility. Where high data rate might normally be implemented by a dedicated hardware it may be decided to implement it by software in areas where a high probability of future change is predicted.

The simulation might be based on information which is either theoretical, empirical or a mixture. The empirical sources are used, for example, to specify target acoustics characteristics. The use of theoretical sources is not quite so straight forward or productive as it might seem at first. The radar is designed primarily for operation in the maritime role and its prime processing function is the elimination of sea clutter effects in accordance with operator selected thresholds. To give the operator the correct 'feel' it is essential that the simulator provides truly representative sea clutter effects to the radar processing system. At first sight the implementation appears to be simple - use the same model for sea clutter which was used for the specifications and development of the prime equipment. However, investigations show that even among the experts there is no agreement as to the details of this model; it would appear that there is no such thing as a 'universal model' for radar sea clutter. One is again in the situation of requiring to use a highly flexible model based upon the prime model but which can be adjusted at a future date to meet the changes required to match airborne performance.

2.5. MODEL VERIFICATION

An essential part of the design and development process is the actual model verification, during which process there is a continual and repeated reappraisal of the following fundamental design criteria:

(1) Is the operational requirement being met?

(2) Has it been correctly engineered?

As far as the first question is concerned, there is a continuously changing design baseline for the simulator as a result of aircraft development and user experience. The second question relates to establishing whether the hardware/software models have been engineered correctly to meet th operational requirement.

During this stage the use of both software and hardware, prototypes, is invaluable. There is often an extensive phase of actually deriving the exact software model during which a whole succession of prototype models may be evaluated and modified or even completely rejected and rewritten. This evaluation process involves comparison of the software model with design source data either theoretically or empirically derived. Prototype hardware is also built. In the early stages this is evaluated step by step, module by module against design data. As this evaluation process proceeds, the prototype is gradually built up in terms of complexity and size aiming towards the final total configuration. Eventually the hardware and software are combined to form a total system and the evaluation and comparison has to be against live data rather than engineering test data. It is at this stage that the use of the actual avionics systems is essential. As an example, the acoustics avionics system is designed to process signals from a very low signal-to-noise ratio environment; the simulator must therefore be capable of operating at corresponding levels. The only piece of test equipment available to operate at such levels is the avionics system itself. Therefore, in this stage, the avionics equipments are used as a set of, albeit highly specialised, test equipments for the evaluation of the simulation. This evaluation is accomplished by comparing the avionics analysis of simulation signals with the avionics analysis of actual signals as obtained during live airborne trials. As necessary, the software and hardware are 'tweaked' or modified to match the trials data. It is at this stage that the efficacy with which the flexibility/ expandability of the model was implemented is appreciated. Through this iterative procedure the design and implementation are perfected.

One of the major difficulties in this verification phase is associated with the highly subjective nature of many of the simulated systems. While there may be little of a subjective nature to actual trials information, and it is possible to set the simulator exactly to match the trials data, the data will have been produced for a limited set of system variables. There is usually neither the money nor the time available to trial the system against all possible combinations of system parameters and consequently it is necessary to interpret performance between the trials points since the simulator must attempt to operate within all combinations. It is this process of interpretation which can be very subjective and makes life so often difficult for the simulator designer. In the final analysis, despite all objective tools used in the interim, it is the assessor's subjective senses which apply the final acceptability criteria.

3. CONCLUSION

It might be worthwhile noting one area of spin-off where useful lessons might be learned for future such programmes. As mentioned earlier in this paper, the actual aircraft system is used as a specialized set of test equipment for the evaluation of the simulator system. Reflection will show that this is the exact reverse of the process used during the development of the aircraft system. Thus during the development of the prime system, there is a need for a signal generator (corresponding to the simulator) for use in evaluating the performance of the aircraft system. The two evaluation processes of aircraft system and simulator are exactly complementary to each other. This has been borne out on the Nimrod programme where the simulator has been used to generate known and controlled signals for stimulation of the acoustics system for evaluation. Had this capability been foreseen at a sufficiently early stage in the aircraft programme the specific requirements for the aircraft system could have been designed into the simulator and a much better and effective tool may well have resulted. The same might apply in the case of radar for evaluating its performance against, for example, jammers. The conclusion then is that although the benefits of early consideration of the simulator in the overall aircraft programme are beginning to become apparent, further scrutiny might reap even more fruitful benefit.

ACKNOWLEDGEMENT

The author wishes to thank the Technical Director of Marconi Electronics Ltd. for permission to publish this paper.

APPLICATION OF COMPUTER SIMULATIONS TO DEVELOPMENT OF NATO E-3A AUTOMATIC TRACK INITIATION ALGORITHMS

E. S. Alvarez and C. J. Sworobowicz
The MITRE Corporation
Bedford, Massachusetts 01730

SUMMARY

The NATO E-3A Airborne Warning and Control System will include the capability to initiate tracks automatically on targets of interest. Due to the complex and interacting nature of the automatic track initiation (ATI) process, development of a prototype ATI design must rely heavily on Monte Carlo computer simulations. Adaptable computer simulations were developed which provide the analyst with a versatile tool for evaluation of ATI design alternatives and performance sensitivities. In addition to assisting the analyst during design development, simulation serves the necessary function of augmenting live testing by providing assessments of system performance in target environments which are difficult or impossible to reproduce in live flight tests or in typical operational exercises. Although the computer simulation was used for the E-3A ATI problem, it also has general application to the evaluation of overall tracking performance for the E-3A or for any track-while-scan system.

The ATI design which evolved from this development effort utilizes a Kalman filter for track smoothing and prediction. A Kalman filter not only provides rapid and accurate determination of target position and velocity, but also provides estimates of tracking errors which can be used to advantage in the design of optimal adaptive correlation windows, maneuver detection thresholds, and track promotion/drop rules. Simulation results have shown that the ATI design provides excellent performance over a wide range of target conditions and target environments.

1. INTRODUCTION

The NATO E-3A automatic track initiation (ATI) function must operate effectively over a wide range of target environments and radar modes. The effects of close formations of targets, maneuvering targets, crossing targets, as well as radar performance characteristics on ATI performance must be considered. Thus, multiple target computer simulations were developed to support the ATI design effort. The ATI function must contend with the conflicting requirements of initiating tracks quickly on real targets and minimizing the number of false track initiations induced by false reports or by radar data contentions between adjacent tracks. A good balance must be achieved between these measures of performance to insure that the ATI function provides effective assistance to E-3A operators. This paper describes the simulation models employed in the development effort, the ATI design which evolved from this effort, and also presents a sampling of the performance characteristics of the prototype design.

The computer simulation contains all the elements necessary to permit a thorough evaluation of prototype ATI designs. The simulation includes target and E-3A flight path generators, radar target detection models, radar false reports, radar measurement errors, track correlation logics, priority rules for resolving track correlation conflicts, track smoothing logics, maneuver detection logics, maneuver response logics, and track promotion/drop logics. A complete set of adaptable parameters are included to permit evaluation of ATI design alternatives and performance sensitivities. Extensive data reduction routines provide comprehensive summaries of pertinent aspects of track initiation and tracking performance.

To maximize the effectiveness of the ATI design in a dense target environment, correlation windows must be small enough to minimize cross-correlations between adjacent targets, yet large enough to provide a high probability of correlating target reports when available. In this type of environment, adjacent target correlation windows will frequently overlap, thus it is important to develop optimally shaped correlation windows augmented by meaningful priority rules for resolving correlation conflicts. The Kalman filter variances are used to advantage in sizing efficient adaptive correlation windows, and these correlation windows are further refined to take full advantage of the fact that the E-3A radar provides very accurate estimates of target range and range rate (in some radar modes). An automatic track drop logic has been developed which makes use of the maximum dimension of the correlation window and thus adapts automatically to individual hit/miss patterns, target range, target report type, and operator entered speed/heading limits. This track drop logic offers a distinct advantage over conventional logics based solely on rigid hit/miss thresholds.

2. ATI SIMULATION MODEL

The computer simulation developed to support the ATI study provides a general tool for evaluating various tracking features of track-while-scan systems. The modular program design provides the analyst with the option to select and tailor program elements appropriate to the problem being studied. The simulation model employs Monte Carlo techniques to generate scan-by-scan simulated radar reports based on true target positions and radar performance parameters. These simulated radar reports are then passed to the tracker model which processes the reports to produce corresponding system tracks. Detailed track histories and events of interest are then recorded for evaluation. Recorded data is available to the analyst in a variety of output options including summary statistics and graphic representations as required to satisfy the objectives of the particular study.

The simulation was developed using FORTRAN IV source code which was compiled and executed on an IBM operating system. Graphic capabilities were provided by a Zeta plotting system; however, the plotting program elements are also compatible with other plotting equipment.

2.1 Computational Support

The simulation model was developed and utilized with an IBM 370/3031 operating system. The basic computer provides 6 million bytes of storage and is interfaced with a complete set of peripheral devices including card reader, high speed printers, tape drives, an extensive direct access storage subsystem for the on-line

storage of data, and display terminals allowing on-line access to the operating system. The entire system operates under the control of IBM's Multiple Virtual Storage (MVS) operating system and can execute 1.2 million instructions per second.

A time sharing option that allows the user to interactively access the operating system with an IBM 3278 display was used extensively during the ATI study. During the model development phase, program elements were composed, edited, compiled, executed and debugged entirely on-line using the time sharing option. After development, program load modules and data sets were retained on disk storage. Simulation production runs were submitted for economical batch execution using the time sharing option.

The data available from the simulation model can be directed to a high speed printer for hardcopy and to a magnetic tape subsystem. The data contained on a magnetic tape can be plotted using the Zeta 6000 Plotting System to pictorially represent simulation results in a clear and concise manner. The Zeta system is an off-line unit which operates independently of the central computer. The system includes a 36 inch incremented drum plotter that operates at speeds up to 4000 increments per second with an incremented size of .0025 inches.

2.2 Key Model Components

The key elements of the ATI simulation are the scenario model, the radar model and the tracker model which generate the true target positions, the simulated radar reports and the track data, respectively. Figure 1 shows the relationship between these models and the data analysis routines included in the computer simulation. Execution of the ATI simulation program may be initiated by inputs to the scenario model or by a tape input to a lower level model. The input tapes in the latter option are obtained by recording options which can save the outputs of any of the component models for subsequent use. For frequently used scenarios or combinations of scenarios and radar parameters, this option permits more efficient use of computer resources.

2.2.1 Scenario Model

The scenario model generates scan-to-scan target and E-3A positions based on model inputs which specify target profiles. A typical profile that was used to support the ATI studies is shown in Figure 2. Targets are identified in the model by a unique number as shown in the figure. The scenario model generates true target positions in range, azimuth and range rate relative to the E-3A. Target maneuvers in speed and/or heading are modelled in accordance with model inputs. Although the E-3A is assumed to fly a racetrack pattern, the model inputs are general enough to permit a wide range of flight paths, including circular orbits and constant velocity flight patterns.

2.2.2 Radar Model

The radar model uses the data provided by the scenario model to generate simulated radar detections on real targets and false reports. The simulation includes two radar models: a constant detection probability (Pd) model and a range dependent Pd model. The constant Pd model is generally used for maritime targets and the range dependent Pd model is used for air targets.

The range dependent model used in the simulation is shown in Figure 3. The curve is approximated in the simulation by selected points and interpolation between adjacent points is performed to determine Pd at any range. The target range has been normalized by the range corresponding to a detection probability of .32 which corresponds to a cumulative probability of .90 of detecting the target within 6 scans (1 minute in the case of the E-3A). The curve is based on theoretical considerations and it adequately represents the actual range dependency of any radar for a constant cross-section target. Various target sizes can be readily simulated simply by changing the range normalization value.

Radar measurement errors are modelled as Gaussian distributed errors in range, azimuth, and range rate (if available). The mean and standard deviation of each of these errors are simulation inputs. The standard deviations are intended to represent the total composite random error in that particular measurement. The radar, of course, is the major contributor to these composite errors. For purposes of this study, E-3A bias errors (primarily navigation errors) are not modelled because they vary slowly with time and thus have no effect on ATI or tracking performance.

Simulated radar reports are generated using Monte Carlo techniques to determine if a target is detected and to determine the magnitude of the error in each of the radar measurements. Independent random number generators are used for measurement errors and are activated even if it has been determined that the target was not detected during that scan. By utilizing random number generators in this manner, analyses of performance sensitivities to various parameters are more meaningful and can generally be accomplished with significantly less Monte Carlo trials.

The radar model also includes a routine for generating false reports which are assumed to be uniformly distributed throughout the surveillance area. For purposes of the study, it is only necessary to model false reports in a relatively small square area which is large enough to include the real targets. The number of false reports within such an area during a particular scan is described by a Poisson distribution. Thus, the number of false reports to be generated (N) can be calculated by:

$$\sum_{k=0}^{N} \frac{\lambda^k}{k!} e^{-\lambda} > RN$$

where, λ = average number of false reports in the square area, i.e., the false report rate multiplied by the ratio of the square area to the surveillance area.

RN = random number draw in the interval (0, 1)

If false reports are present during a given scan, the positions of these false reports are determined by two random number draws in X and Y coordinates relative to a corner of the square. If the report is to simulate the radar pulse doppler mode, a range rate value is also generated. The range rate value is assumed to be Gaussian distributed.

2.2.3 Tracker Model

The tracker model uses the scan-to-scan simulated radar detections provided by the radar model as inputs to the tracking process. This model includes all the elements necessary to initiate tracks automatically and to perform all the functions inherent in the tracking process. All the component features of the tracker model are described in paragraph 3.

The tracker model employs a variety of model inputs which control correlation window sizes and ATI promotion/drop criteria. The basic tracker functions of track initiation, Kalman filter initialization, track correlation, resolution of target report contentions, and track smoothing are modelled by independent routines. Thus the tracker model can be readily reconfigured to evaluate alternative designs.

2.3 Simulation Model Inputs

Model inputs are used to tailor the simulation model to the problem being studied and to provide control over key parameters used for performance sensitivity analyses. These inputs are stored on disk in a file that can be edited on-line prior to submitting a computer run. Some of the basic inputs to the simulation model are listed below:

Control Inputs

NMCR = number of Monte Carlo trials
NMAX = number of radar scans to be simulated during each Monte Carlo trial
NSKP = flag used to control output options
MODE = flag used to control radar mode simulated

Scenario Model Parameters

LENGTH, RADIUS, VA, HA = E-3A racetrack parameters and E-3A speed and heading
XTO, YTO = initial target position (X and Y coordinates)
VT(I), HT(I) = target speed and heading at the start of each new leg
ACCEL(I), TIME(I) = acceleration value used for each target maneuver and start time for the maneuver
NTGT = number of real targets in the scenario

Sensor Model Parameters

PDO = single scan probability of detection for the constant Pd radar model
PD(I) = table entries for range dependent Pd radar model
RO = normalization range for range dependent radar model
SIGR, SIGAZ, SIGRD = radar measurement error variances in range, azimuth and range rate, respectively
FAR = false report rate per scan
FARBOX = dimension of square area within which false reports are generated
XO, YO, VB, HB = position, speed and heading of the center of FARBOX

Tracker Model Parameters

CM(I) = various multipliers used to size range, azimuth and range rate correlation windows for potential, tentative and established tracks
DRD = potential track correlation window for range rate
V1, V2 = assumed track speed limits entered by E-3A operator
H1, H2 = assumed track heading limits entered by E-3A operators
N2 = number of scans without a correlation before a potential or tentative track is automatically dropped
N1 = number of correlations required to promote a tentative track to an established track
RMAX = maximum radius allowed for the correlation window before a tentative track is dropped
RMAXP = same as above for potential tracks

2.4 ATI Model Outputs

ATI model outputs are provided by high speed printing or off-line plotting equipment. Printouts include scan-to-scan data and event histories, track summaries, and ATI performance statistics. The type of printed output desired is specified at the time of program execution by appropriate input control parameters. Four types of printed output are available and examples of each are presented in Figures 4 - 7. An example of the plotted output available is shown in Figure 8. These examples were generated during a 100 scan simulation run using the 20 target geometry depicted in Figure 2, target speeds of 500 knots, and the range dependent probability of detection radar model.

For each Monte Carlo run, the data shown in Figure 4 is available for every simulated radar scan. The data is divided into two basic sections: a target data summary and a track status summary. The target data summary includes the actual target X and Y coordinates and the radar reported target coordinates in X, Y, and $\dot{R}$. An entry of zero for a target radar report indicates that the target was not detected during that scan. Real targets are numbered sequentially (1 through 20 in this example) and this number is retained as a unique identifier for the target. False reports (if any) generated by the radar are printed out immediately below the true target reports (target number 21 in Figure 4).

The track status summary is the second basic section in Figure 4. The first printed line beside the title provides a summary count of tracks in potential, tentative, established, or drop status. Data is shown for each track currently in the system ordered by track number. Track numbers are assigned sequentially, starting with one, as each new track is initiated. Track data in this summary includes the initiation status of the track (P = potential, T = tentative, E = established, D = dropped), the target number of the report used to update the track during the current scan, and the target number of the report which was previously used to update the track. An entry of zero in column 2 indicates that a target report did not correlate with the track that scan, while an entry of 99 indicates that the track has just been automatically dropped. These entries are followed by tracking errors in position (X component, Y component, total position error), speed, and heading. The predicted range, azimuth and range rate of the track are printed out in the next three columns. If a report correlated with a particular track during the current scan, its range, azimuth, and range rate are printed out in the next three columns. The remaining entries include the range, azimuth, and range rate correlation window sizes, the X and Y position of the predicted track, and X and Y measurement residuals. The measurement residuals are the differences between the reported target position and the predicted track position.

In the example shown in Figure 4, track number 8 has just been promoted to established status. It should be noted that its current correlation was with target number 14 and its previous correlation was with target number 13. This is an example of a false track resulting from cross-correlations in the tentative phase. Typically, such a track has a relatively large speed and heading error, and fails to correlate consistently with any target after the cross-correlation has occurred.

Figure 5 is an example of a printout which provides a cross reference of target and track numbers on a scan-to-scan basis. This printout is provided for each Monte Carlo run. The first column of the printout is the scan number associated with each row of data. Columns 2 through 21 correspond to target numbers 1 through 20, respectively, and columns 22 through 26 are for false reports. The number entry appearing in a target report column corresponds to the number of the track which was updated by that particular target during the current scan. An entry of zero indicates that the target was not detected during that scan. The matrix representation shown in this figure is especially useful because the analyst can quickly determine how soon a track is initiated on a target and how well the target is being tracked. In addition, false tracks resulting from cross-correlations between targets can be easily identified. The example shown in Figure 5 shows two such false tracks, namely track numbers 2 and 8. Track number 8 was promoted to an established track during scan 6 after correlating on reports from target numbers 12, 13, and 14; and track number 2 was promoted during scan 7 after correlating on reports from target numbers 1 and 2.

Scan-to-scan histories of each track for each Monte Carlo run are also available to the analyst. As an example, the history for track number 2 (i.e., the false track discussed in the previous paragraph) is shown in Figure 6. The track data is ordered according to scan number (shown in column 1) commencing with the scan number when the track was initiated as a potential track. Column number 2 indicates the current initiation status of the track and column 3 gives the number of the target which has updated the track. A zero entry in column 3 indicates that the track was not updated that scan. The remaining information in this printout is a subset of the data shown in the track status summary section of Figure 4.

Figure 6 shows that a potential track was initiated on target 2 during scan 1. The track was promoted to tentative status during scan 2 based on a correlation from target 2. The next correlation (scan 3) was also from target 2 but the following correlation at scan 7 which resulted in promotion to established status was from the adjacent target number 1. The reason for the cross-correlation is that the speed and heading errors are rather large, due primarily to unusually noisy radar measurements in the first two reports. The large speed and heading errors eventually cause the track to lose correlation on its own target and move close enough to the adjacent target to result in a cross-correlation.

Summary statistics as shown in Figure 7 are available for each Monte Carlo run. This summary includes the number of false tracks, the number of lost tracks (i.e., established tracks which are no longer being updated by the target which initiated the track), plus pertinent information on the valid tracks initiated by the ATI function. Summary statistics identical to the Figure 7 format are also provided for the composite set of Monte Carlo runs.

The track data generated from a multiple target simulation is sometimes difficult to visualize from printed outputs alone. Consequently, a routine was developed to provide the capability to plot tracks and radar reports. The output from the tracker model saved on magnetic tape includes all the track and report data required as input to generate a plot. The plot routine requires additional input parameters to control the scale of the plot, to select the scan of interest, and to select the tracks for which correlation histories are desired along with the number of scans desired in this correlation history. An example of a plot generated using this capability is shown in Figure 8.

All tracks depicted in Figure 8 are tagged with their respective track numbers for easy identification. The initiation status of each track is given following the track number (P = potential, T = tentative, E = established, D = dropped). Individual radar reports correlating with selected tracks during the seven previous scans may also be plotted. Figure 8 depicts the report histories for the two false tracks (numbers 2 and 8). These reports are connected by broken lines and labelled with the target number which they represent. The target numbers are subscripted with the scan number during which the target was detected. The vectors shown as solid lines originating from each track position indicate the track velocity. The magnitude of the vector is scaled to the track speed and the direction of the vector indicates the track heading.

2.5 Timing and Sizing Estimates

The simulation model which was generally used during the ATI studies had a 20 target capacity, although a 100 target capacity model was also used to some extent. The 20 target simulation model required 120,000 bytes of storage on the IBM 370/3031 computer (8 bits/byte) while the 100 target model required 150,000 bytes of storage.

The execution time for an ATI simulation run is a function of obvious parameters such as number of targets, number of scans, and the number of Monte Carlo runs. Execution time varies linearly with these parameters. However, the selected printout option also has significant impact on execution time. Table 1 presents the execution time for the three available options (which are various combinations of the printout examples shown in Figure 4 through 7). The times shown in the table correspond to a 20 target scenario, 100 scans, and 10 Monte Carlo runs. Printout option A includes the track/target correlation matrix shown in Figure 5 plus the summary statistics shown in Figure 7. Option A produces 2 pages of printout per Monte Carlo run. This printout option is usually sufficient to evaluate performance of a mature ATI design. During the development phase of an ATI design, however, more extensive data outputs are often required and printout options B and C are available to assist the analyst. Printout option B includes the output of option A plus the scan-to-scan report and track summaries shown in Figure 4. Option B produces 102 pages of printout per Monte Carlo run. Printout option C provides the output of option B plus the track histories shown in Figure 6. Option C typically produces 140 pages of printout per Monte Carlo run. The processing time associated with the scenario model and the radar model is less than 5 seconds for the example shown. This is attributed to the rather simple 20 target scenario considered. More complex scenarios with maneuvering targets would require more processing time. For such scenarios, it is worthwhile to use the tape recording options for scenario model or radar model outputs and save this processing time during subsequent computer runs.

TABLE 1

TIMING ESTIMATES

Printout Option	Time (Seconds)
A	96
B	260
C	301

3. ATI DESIGN

The ATI design employs three distinct tracking phases, namely potential, tentative, and established. A potential track is formed from reports which do not correlate with tentative or established tracks. A potential track is promoted to tentative status if a report correlation is achieved within a certain time period, otherwise the track is dropped. Upon promotion to tentative an initial track velocity can be calculated from the ground stabilized position coordinates of the target report pair. The tentative track is promoted to established status when subsequent correlations suggest that the track probably represents an actual target. A tentative track is dropped if timely report correlations are not achieved. A Kalman filter is employed for track smoothing and to assist in sizing efficient correlation windows.

All pertinent algorithms and logics characterizing the ATI function of the E-3A tracker are described in this section. A flowchart has been included in Figure 9 to assist the reader in understanding the overall structure of the integrated ATI/tracker design.

3.1 E-3A Radar Operating Modes

The E-3A detects air and maritime targets in a variety of modes; namely, radar air mode, radar maritime mode, and IFF. The radar air mode produces two different types of reports, pulse doppler (PD) reports and beyond-the-horizon (BTH) reports. The radar PD mode is the normal E-3A mode which provides detections on targets out to the limits of its detection range. The PD report includes estimates of target range, azimuth, and range rate. The radar BTH mode augments the E-3A surveillance volume by providing detections on targets beyond the range of the PD mode. The BTH report includes estimates of target range and azimuth. The radar maritime mode provides detections on maritime targets within line-of-sight of the E-3A, and the report includes estimates of target range and azimuth. The IFF sensor (its antenna mounted back-to-back with radar antenna) provides estimates of target range and azimuth, along with the associated IFF modes and codes on all transponder equipped air and maritime targets in the E-3A surveillance volume. Automatic initiation of targets detected by IFF is considerably easier than for radar targets since IFF reports include mode and code identifying information which can be used to advantage in discriminating between nearby targets. Thus, the primary emphasis of this paper is ATI processing of radar reports.

It is advantageous to totally segregate the air and maritime ATI functions. This prevents unnecessary degradation in ATI performance due to targets or false reports of the opposite type. Unique identifier bits in the target report word are used to maintain this segregation. These identifiers are also used to key other unique processing features in the ATI design.

3.2 ATI Track Phases and Promotion Rules

The ATI function employs two intermediate track categories (potential and tentative) enroute to establishing a new system track. Potential tracks are initiated on candidate sensor reports located in operator defined ATI areas which do not correlate with tentative or established tracks. Candidate reports are determined by the type(s) of reports selected by the E-3A operator for the particular ATI area, i.e., radar (air mode), radar (maritime mode), and/or IFF.

A potential track is initiated at the location of the target report with zero speed. If the report is a maritime target detection, the maritime Kalman filter is initialized and normal Kalman smoothing commences with the next correlation. If the report is an air target detection, initialization of the air tracker is delayed until the next correlation when a velocity can be calculated.

If a report correlates with a potential track during a subsequent scan, the track is promoted to tentative status. For air targets, the tentative track is initiated at the position of the current report with a velocity calculated from the two reports now available on the target and the elapsed time between reports. The air tracker is initialized and normal Kalman smoothing commences with the next correlation.

Tentative tracks are promoted to established status if N1 reports correlate with and are used to smooth the tentative track, and if track speed and heading (speed only for maritime tracks) fall within operator entered limits. For maritime targets and for air targets detected in the radar PD mode, a value of two (2) has been used for N1. For air targets in the radar BTH mode, a value of three (3) is used for N1. The N1 correlations must be achieved in a timely manner otherwise the track is dropped automatically. Track drop rules for tentative tracks are discussed in paragraph 3.6. While in the tentative phase (also for the potential phase of maritime tracks), track smoothing and prediction logics are the same as those used for established tracks, but the correlation logic (described in paragraph 3.3 and 3.4) is somewhat different.

3.3 Correlation of Target Reports with Air Tracks

The development of effective correlation tests for potential air tracks is difficult because there is no velocity estimate available until a pairing is achieved. The simplest correlation window which could be used for potential tracks is a circular window centered at the track position with a radius determined by the maximum possible target speed plus an allowance for measurement errors. Such a window could be quite large and thus require unnecessarily stringent track promotion/drop rules to minimize the number of false tracks. More effective correlation tests can be devised by taking advantage of operator entered target speed/heading limits, and target report range rate (if the target is detected in the radar PD mode). The use of target speed/heading limits in shaping position correlation windows is discussed in paragraph 3.3.1 and the use of target range rate for further correlation testing is discussed in paragraph 3.3.2. For tentative air tracks, the correlation window design takes advantage of the fact that radar measurements of target range are very accurate in comparison to the azimuthal measurement and also makes use of range rate if available. Correlation windows for tentative air tracks are discussed in paragraph 3.3.3.

3.3.1 Position Correlation Windows for Potential Air Tracks

The position correlation window used for potential air tracks (see Figure 10) takes advantage of operator entered speed/heading limits. The window is sized as follows:

If,

V_1, V_2 = operator entered speed limits for ATI region

H_1, H_2 = operator entered heading limits for ATI region

R = target range

σ_θ = standard deviation of measurement error in target report azimuth

ΔT = elapsed time since potential track was initiated

Then, the potential track correlation window is sized as follows:

$$H_o = \frac{(H_1 + H_2)}{2}$$

$$D_o = \frac{(V_1 + V_2)\,\Delta T}{2}$$

$$\Delta D = \frac{(V_2 - V_1)\,\Delta T}{2} + K\,(R\,\sigma_\theta)$$

$$\Delta H = \frac{(H_2 - H_1)}{2} + \frac{K\,(R\,\sigma_\theta)}{D_o}$$

The second term in the expression for ΔD and ΔH is an allowance which compensates for measurement errors. Only the effect of the azimuthal error need be included since it predominates. The multiplier, K, is an optimization parameter and a value of one has been used.

If,

X_2, Y_2 = coordinates of report for which correlation is being attempted

X_1, Y_1 = potential track position, i.e., coordinates of first report

Then the candidate report is correlated with the track if:

$$\left| \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} - D_o \right| \le \Delta D$$

and

$$\left| \tan^{-1}\left(\frac{X_2 - X_1}{Y_2 - Y_1}\right) - H_o \right| \le \Delta H$$

3.3.2 Range Rate Correlation and Compatibility Tests for Potential Air Tracks

In addition to the position correlation tests described above, air targets detected in the radar PD mode are subjected to a range rate correlation test and a range rate compatibility test. The range rate correlation test is simple to implement and provides effective discrimination against nearby targets moving at different speeds and targets moving at the same speed but at different headings. The test simply requires that the target report range rate be within a prescribed tolerance of the range rate in the report used to initiate the potential track.

The range rate compatibility test provides effective discrimination against nearby targets moving at the same speed and heading. This test is implemented by requiring that the target report range rate be within a tolerance value of the estimated range rate computed from the track velocity components. The test is implemented as follows:

If,

X_1, Y_1 = potential track position, i.e., coordinates of first report

$X_2, Y_2, \theta_2, \dot{R}_2$ = X, Y coordinates, azimuth and range rate of report for which correlation is being attempted

ΔT = elapsed time since potential track was initiated

σ_R = standard deviation of measurement error in target report range

$\sigma_{\dot{R}}$ = standard deviation of measurement error in target report range rate

$\dot{R}_c$ = estimated track range rate

Then,

$$\dot{X} = \frac{X_2 - X_1}{\Delta T}$$

$$\dot{Y} = \frac{Y_2 - Y_1}{\Delta T}$$

$$\dot{R}_c = \dot{X} \sin \theta_2 + \dot{Y} \cos \theta_2$$

Using analysis of variance techniques, it can be shown that the range rate tolerance which should be used for the compatibility test takes the form,

$$\left(\dot{R}_{TOL}\right)^2 = K \left[2 \left(\frac{\sigma_R}{\Delta T}\right)^2 + \sigma_{\dot{R}}^2 \right]$$

where K is an optimization parameter with a value of four. The candidate report is then correlated with the potential track if,

$$\left|\dot{R}_2 - \dot{R}_c\right|^2 \leq \left(\dot{R}_{TOL}\right)^2$$

3.3.3 Correlation Windows for Tentative Air Tracks

The track correlation logic used for tentative air tracks can be simpler than that used for established tracks. Established tracks use dynamically sized correlation windows supplemented by smaller non-maneuver windows to perform track correlation. Non-maneuver windows are used to determine if target reports are from a non-maneuvering target or a maneuvering target. Non-maneuver windows are oriented in range and azimuth relative to the E-3A to take advantage of the fact that the range measurement is much more accurate than the azimuth measurement. These non-maneuver windows are dynamically sized as a function of the error estimates provided by the Kalman filter and the sensor measurement variances modelled in the tracker. With slight modification to window multipliers, established track non-maneuver windows can be used for tentative track correlation windows. The multipliers selected for tentative tracks are 2σ in the azimuthal dimension, 4σ in range, and 8σ in range rate. The correlation window is shown in Figure 11. Larger multipliers are required for range and range rate windows to maintain correlation on targets undergoing modest maneuvers. These windows are adequate for most scenarios but initiation of targets undergoing severe maneuvers could be delayed. The 2σ azimuth windows provide a 95% chance of correlating reports from non-maneuvering targets. For maneuvering targets, the probability will be reduced somewhat depending upon the magnitude and severity of the maneuver and the time elapsed since the last detection. If track correlation is lost on maneuvering targets, the tentative track would probably end up being dropped or would jump to an uncorrelated report on another target. However, Kalman filter gains are quite large during the tentative track phase and, therefore, the tracker has an inherent capability to follow many types of maneuvers without resorting to a dedicated maneuver detection/response logic.

3.4 Correlation of Target Reports with Maritime Tracks

Maritime track correlation windows, like air track tentative windows, take advantage of the fact that the range measurement is much more accurate than the azimuth measurement. However, since maritime targets travel such small distances between scans in comparison to radar measurement errors, an accurate determination of track velocity is not possible during the ATI phase of tracking. Hence, maritime correlation windows must be increased in size to account for the possibility that the maritime target is moving at very high speed. The correlation window thus used for potential and tentative maritime tracks takes the form:

$$\Delta R = \Delta R_o + V_{max} \Delta T$$

$$\Delta \theta = \Delta \theta_o + \frac{V_{max} \Delta T}{R}$$

where,

ΔR_o = 4σ range window described in paragraph 3.3.3

$\Delta\theta_o$ = 2σ azimuth window described in paragraph 3.3.3

V_{max} = maximum expected speed for maritime target

ΔT = elapsed time since last correlation

R = target range

The second term in the equations for ΔR and $\Delta\theta$ is the tolerance which must be added to account for the fact that the initial speed estimate of zero could be in error by as much as V_{max} knots. It should be noted that the use of this added tolerance will permit a better maneuver following capability in the potential and tentative track phases than is possible for air targets. The correlation window is shown in Figure 12.

3.5 Selection of Best Correlating Report

The ATI function selects the single "best" report for tracks except that reports eligible for correlation with potential tracks will be limited to reports that have not correlated with tentative or established tracks. The best report is the report which is closest, in a normalized sense, to the center of the correlation window. The measure of closeness is calculated as follows:

$$TQ = \frac{(\Delta R)^2}{\sigma_R^2} + \frac{(\Delta\theta)^2}{\sigma_\theta^2} + \frac{(\Delta\dot{R})^2}{\sigma_{\dot{R}}^2}$$

where, ΔR, $\Delta\theta$, $\Delta\dot{R}$ represent the measurement residuals.

In addition, the ATI function does not permit a report to update more than one track. Target report contentions are resolved using the TQ value calculated above to select the best track/report pair. Tentative and established tracks have equal priority in the best pair selection logic.

3.6 Track Drop Rules

Potential and tentative tracks should be dropped when it is determined that there is high likelihood that the track will not result in a valid track. Logics used by existing systems with ATI functions use hit/miss ratios as a measure of track quality. However, a Kalman filter tracker, through its covariance matrices, provides an inherent capability to estimate track quality directly and this can be used to advantage in developing track drop rules.

As mentioned in paragraph 3.3.3, Kalman filter covariances and measurement error variances are used to size the range, azimuth, and range rate tentative track correlation windows. The behavior of the air track azimuthal correlation windows (for a measurement error variance equal to that produced by the radar PD mode) as a function of time is depicted in Figures 13, 14, and 15 for various hit/miss patterns. The hit/miss patterns are shown in the legend where "x" corresponds to a correlation and "o" corresponds to a missed correlation. Figure 13 is for a tentative track initiated at scan 2 as a result of 2 successive reports on the target. Figure 14 is for a tentative track initiated as a result of 2 reports on the target in 3 scans, and Figure 15 is for a tentative track initiated as a result of 2 reports in 4 scans. The reason that the correlation windows in Figures 14 and 15 are smaller is that the 2/3 and 2/4 tentative track pairings permit a more accurate velocity determination than the 2/2 tentative track pairing and this improvement is reflected as a reduced expansion rate in the correlation window. The range and range rate correlation windows would vary in similar manner to the azimuthal window. For maritime tracks the corresponding correlation windows would be smaller than air track windows by about a factor of two.

A key factor in minimizing false tracks is to insure that correlation windows do not get too large. This suggests that tentative tracks should be dropped when correlation windows exceed some predetermined limit. The drop logic which was implemented for tentative tracks compares the larger dimension of the correlation window (azimuthal dimension in nmi) with an input value RMAX. If this value is exceeded, the tentative track is dropped. The comparison is done after track correlation, hence the correlation window is allowed to exceed RMAX for one scan. A value of 6 nmi has been selected for RMAX. It is prudent to override the RMAX track drop rule after a relatively large number (say N2) of successive misses, thus tentative tracks are dropped after six successive misses even if the correlation window is less than RMAX. Given this value of N2 and a detection probability of 0.3, only about 10% of the tentative tracks on real targets would be dropped prematurely. At higher detection probabilities, the percentage of prematurely dropped tracks is insignificant.

Early simulation testing suggested that the RMAX track drop rule described above could also be used to advantage for potential tracks. In this case, the correlation window dimension used for comparison is:

$$D = \begin{cases} V_2\ \Delta T \sin\left(\frac{H_2 - H_1}{2}\right) + K\left(R\ \sigma_\theta\right) & \text{for } \Delta H < 90^\circ \\ V_2\ \Delta T + K\left(R\ \sigma_\theta\right) & \text{for } \Delta H \geq 90^\circ \end{cases}$$

using the notation in paragraph 3.3.1. Since H_1 and H_2 are fixed for a ATI region, the sine function in the expression need be calculated only once.

In order to better appreciate the effect of the RMAX track drop rule on potential air tracks, consider some examples of correlation window sizes as a function of time since track initiation. Figure 16 shows the potential track correlation window dimension (D in equations above) for operator entered upper speed limits (V_2) of 1000 and 2000 knots, for a target at fighter detection range, for the PD azimuth measurement error variance,

and for various operator entered heading limits. So, for example, if RMAX = 6 nmi and $\Delta H = 45^{o}$, up to two misses would be permitted for V_2 = 1000 knots but no misses would be permitted for V_2 = 2000 knots.

The ATI track drop logic described above provides an optimum control logic which insures that false track initiation rates are relatively constant as target and sensor conditions change. The logic offers a distinct advantage over conventional logics based on hit/miss thresholds, because it adapts automatically to individual target hit/miss patterns, target range, target report type, and operator entered speed/heading limits. The values of N1 (number of hits to establish) and RMAX were selected to provide the desired balance between false track initiations and valid track initiations. Once established, this pair of numbers provides an optimum balance for a variety of target geometries and sensor characteristics.

In addition to sizing potential track correlation windows, operator entered speed and heading limits (with appropriate tolerances) are used as a final check on air tracks before promotion. If promotion rules have been satisfied but the track is not within appropriate speed and heading limits, the tentative track is dropped. For maritime tracks only a speed check is made to drop tracks which are moving faster than the maximum expected maritime target speed. Early simulation results have shown that this final check is useful in discarding some of the false tracks which result from cross-correlations in the tentative phase. Cross-correlations in this phase usually result in velocity distortions which are severe enough to place the track outside speed and/or heading limits. Obviously, some real tracks could be dropped by this test, but simulation results have shown that this is a rare occurrence.

3.7 Track Smoothing

The ATI function employs decoupled 2 x 2 Kalman filters (X, $\dot{X}$ and Y, $\dot{Y}$ coordinates) for smoothing ATI tracks. The Kalman filters are identical to those used for established tracks thus assuring a smooth transition of ATI tracks to established status. For air targets, a track is initialized upon promotion to tentative status using the velocity computed from the two reports on the target. The air track Kalman filters are also initialized at this time using appropriate variances. For maritime targets, the track is initialized at zero speed and its Kalman filters are initialized when the potential track is initiated. Track smoothing commences at the time of the next correlation.

3.8 Track Prediction

Track prediction is performed in standard manner by linearly extrapolating the X and Y track position to the time of the next expected target report using the current estimate of track velocity. The corresponding values of predicted range, azimuth, and range rate must take into account the fact that the E-3A is moving. Extrapolation of the most current E-3A navigation data yields the estimate of E-3A position necessary to calculate these predicted values. Since more current navigation data is available at the time of correlation and smoothing, errors introduced by E-3A maneuvers are minimized.

3.9 Established Track Processing

The only basic difference between established and tentative track processing logics is that established tracks employ a dedicated maneuver detection/maneuver response function. Non-maneuver windows supplemented by larger correlation windows are used to perform the maneuver detection function. When a maneuver is confirmed, a special maneuver response logic is employed to update the track.

4. SIMULATION RESULTS

The ATI design described in Section 3 was evaluated using a variety of non-maneuvering and maneuvering target raid formations. A sampling of initiation performance is presented in this section. The behavior of the ATI design is controlled almost entirely by the values for N1 (number of correlations in tentative phase required to promote), N2 (maximum number of misses allowed in potential or tentative phases), and RMAX (drop criterion based on correlation window size). Recall that a potential or tentative track is dropped after an unsuccessful correlation attempt if the wider dimension of the correlation window exceeds RMAX nmi. The standard values used in the simulation were:

$$N1 = 2$$
$$N2 = 6$$
$$RMAX = 6 \text{ nmi}$$

The results presented are for the 20 target formation shown in Figure 2 with target spacings of about 5 nmi. All targets in the formation move at the same speed and heading thus presenting a worst case situation for the ATI function. For air targets, the radar model depicted in Figure 3 was used and the initial target ranges were near a normalized range of 1.0. For maritime targets the constant single scan detection probability radar model was used and the initial target ranges were near line-of-sight range to the horizon.

4.1 Non-Maneuvering Air Targets

Figure 17 depicts initiation performance for 500 and 2000 knot fighter target formations. The performance sensitivity to target azimuth (θ in Figure 2) is also shown. Performance is expressed in terms of percent tracks initiated as a function of time since the start of the simulation, averaged over 10 Monte Carlo trials. A target is considered initiated at the time of promotion to established status, i.e., after four correlations on the target. Thus the earliest possible initiation is at .67 minutes (four scans) if four successive detections are made on the target.

The higher speed targets are initiated faster because detection probability increases faster than for low speed targets. As expected, speed of initiation is more sensitive to target azimuth at the lower target speeds, with the 180^{o} target azimuth (i.e., tail chase geometry) being the worst case. For this azimuth, closing speed on the E-3A is minimized, thus the target spends much of its time in the low probability of detection region. At the higher target speed the speed of initiation is insensitive to target azimuth.

Other performance parameters of interest are shown in Table 2 below for each of the two target speeds. The table entries represent averages over the five azimuths for 10 Monte Carlo trials. The entry for "track initiation attempts" represents the average number of track initiation attempts on the 20 targets, thus 61 (81 minus 20) of the potential tracks initiated on the 500 knot targets were dropped sometime during the ATI phase versus 33 (53 minus 20) of the potential tracks initiated on the 2000 knot targets. The reason that the number is so much higher for the low speed targets is that their lower closure rates with respect to the E-3A results in lower detection probabilities. These lower detection probabilities in turn, require more initiation attempts before the initiation criteria are satisfied. The second entry in the table is the maximum number of tracks (sum of potential, tentative, and established tracks) which exist simultaneously. This number is important because it provides an indication of the track storage required for ATI tracks over and above the track capacity for established tracks. The third entry represents the percentage of established tracks which are valid, where a valid track is defined as a track promoted to established status based on detections from the same real target. This last entry is, of course, a key measure of performance for an ATI function because the number of false tracks (related to the complement of the entry) represents an added workload for surveillance operators.

TABLE 2

OTHER ATI PERFORMANCE PARAMETERS (AIR TARGETS)

	Target Speed	
	500 Knots	2000 Knots
Number of Track Initiation Attempts	81	53
Maximum Number of Simultaneous Tracks	25	24
Valid Track Initiation Ratio (Percent)	97	98

4.2 Non-Maneuvering Maritime Targets

Figure 18 depicts initiation performance for maritime targets as a function of probability of detection (Pd). The figure represents an average of high and low target speed performance since performance is very insensitive to target speed.

Table 3 lists the other performance parameters of interest. The entries for "track initiation attempts" and "simultaneous tracks" should not be compared directly to the equivalent entries for air tracks since false report rates are much higher in the maritime radar mode. Even with the higher false report rates, initiation of maritime targets is a much easier problem (as reflected by the very high valid track initiation ratios) because targets move very slowly, thereby minimizing target interference effects.

TABLE 3

OTHER ATI PERFORMANCE PARAMETERS (MARITIME TARGETS)

	Pd		
	.3	.5	.9
Number of Track Initiation Attempts	59	53	55
Maximum Number of Simultaneous Tracks	32	31	32
Valid Track Initiation Ratio (Percent)	99	99	100

4.3 Maneuvering Air Targets

The correlation windows for tentative tracks must be large enough to accommodate target maneuvers without degrading the capability to discriminate against nearby targets. The correlation windows described in paragraph 3.3.3, i.e., 2σ in azimuth, 4σ in range, 8σ in range rate provide a good compromise. It was found that ATI performance on maneuvering targets (Figure 2 geometry with 20° dog-legging maneuvers every 2 minutes) was virtually identical to the performance shown in paragraph 4.1 for non-maneuvering targets. Significant degradations in ATI performance are not expected until maneuvers begin to exceed 50° for low speed targets and 25° for high speed targets.

5. CONCLUSIONS

A multiple target tracking Monte Carlo simulation model was developed to support ATI studies for the NATO E-3A. The simulation model was essential to support this effort, since performance of an ATI function is very dependent upon the target environment, the false report environment, and the inter-target dynamics. The simulation model is readily adaptable and can be used to explore a variety of ATI design alternatives. Furthermore, the model has general application to the evaluation of all aspects of tracking performance for the E-3A or for any track-while-scan system.

The ATI studies have shown that cross-correlations between adjacent targets are a potentially serious problem and conscious efforts must be made to minimize their occurrence. Cross-correlations are the dominant cause of false tracks and they also delay initiation of tracks on real targets. The ATI design described in this paper employs several unique features which effectively minimize the effect of nearby targets. The design achieves a good compromise between speed of track initiation and false track initiation rates.

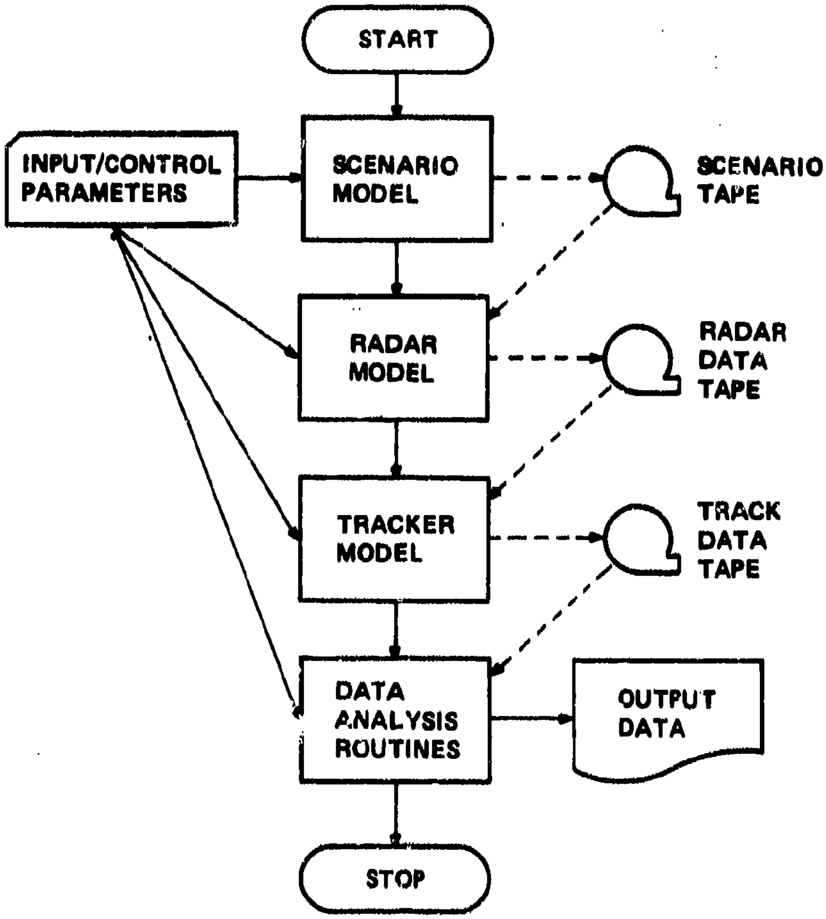


Fig.1 Simulation model

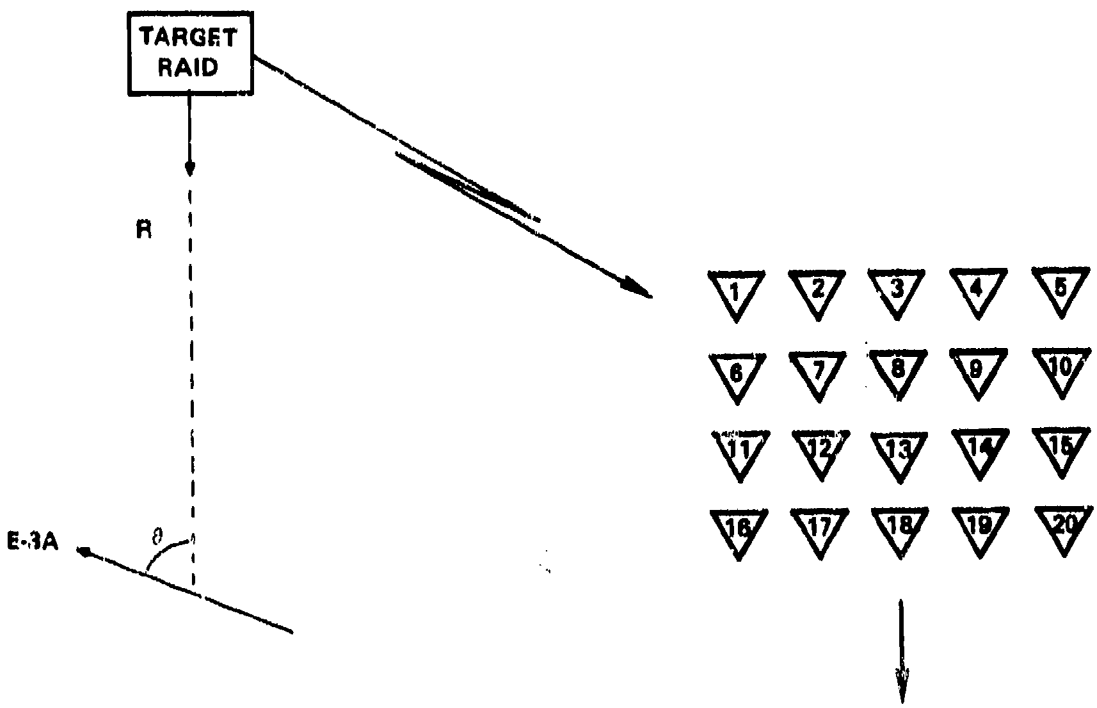


Fig.2 Target geometry

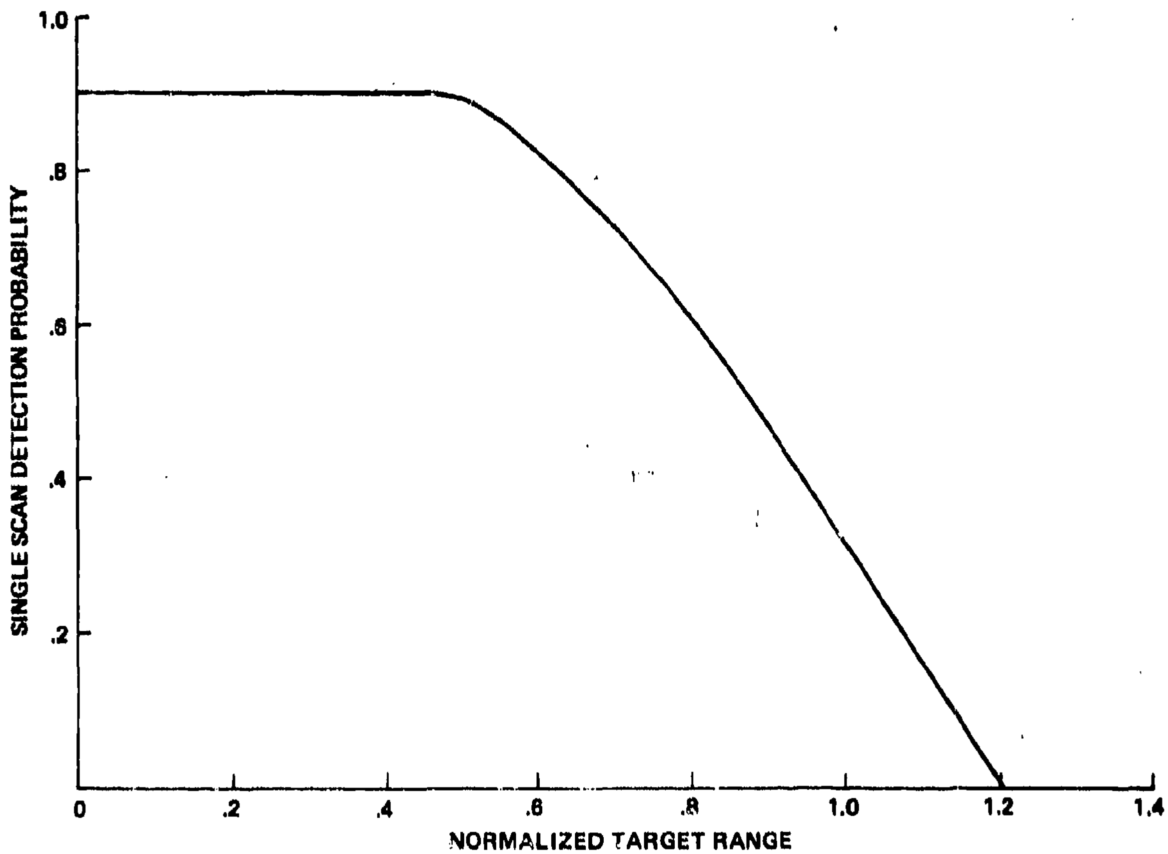


Fig.3 Radar detection probability versus target range

*****MONTE CARLO TRIAL NUMBER 4*****RADAR SCAN NUMBER 6*****

TARGET DATA:

TARGET #	ACTUAL TARGET POSITION X POSITION	Y POSITION	TARGET RADAR REPORTS X POS	Y POS	RANGE RATE	FALSE RADAR REPORTS X POS	Y POS	RANGE RATE
1	-8.00	247.06	0.0	0.0	0.0			
2	-4.00	247.06	0.0	0.0	0.0			
3	0.00	247.06	-0.56	247.12	-493.0			
4	4.00	247.06	0.0	0.0	0.0			
5	8.00	247.06	8.41	246.92	-495.9			
6	-8.00	243.06	0.0	0.0	0.0			
7	-4.00	243.06	-3.40	242.97	-506.3			
8	8.00	243.06	0.00	242.98	-501.9			
9	4.00	243.06	0.0	0.0	0.0			
10	8.00	243.06	7.65	243.08	-504.9			
11	-8.00	239.06	-7.94	239.16	-496.0			
12	-4.00	239.06	-4.31	238.93	-504.9			
13	0.00	239.06	0.0	0.0	0.0			
14	4.00	239.06	3.12	239.05	-485.2			
15	8.00	239.06	8.39	238.99	-505.0			
16	-8.00	235.06	-8.55	235.08	-494.3			
17	-4.00	235.06	-3.67	235.06	-506.7			
18	0.00	235.06	0.0	0.0	0.0			
19	4.00	235.06	3.58	235.02	-513.9			
20	8.00	235.06	7.27	235.18	-499.5			
21						-6.78	234.61	-434.95

TRACK STATUS SUMMARY: 2 POTENTIAL (P), 5 TENTATIVE (T), 14 ESTABLISHED (E) AND 1 DROPPED (D) TRACKS

*****TRACK***** ****PREDICTED**** ****REPORTED**** ****GATES**** **PRED/RPRT RESIDUAL****

1-TRACK NO. 5-X ERROR 8-SPEED ERR 10-RANGE 13-RANGE 16-RANGE 19-X PREDICTION
2-TRACK STATUS 6-Y ERROR 9-HEADNG ERR 11-AZIMUTH 14-AZIMUTH 17-AZIMUTH 20-Y PREDICTION
3-TARGET NO. 7-POSITION ERROR 12-RANGE RATE 15-RANGE RATE 18-RANGE RATE 21-X RES
4-LAST TARGET NO. 22-Y RES

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	E	0	1	-0.2	-0.2	0.3	12.	1.	177.1	-0.0466	-511.				0.6	0.0176	61.	-8.2	246.9		
2	T	0	2	-3.5	-0.1	3.5	98.	31.	177.1	-0.0424	-502.				0.6	0.0185	54.	-7.5	247.0		
3	E	3	3	-0.3	0.0	0.3	-2.	-1.	177.0	0.0000	-503.	177.1	-0.0032	-493.	0.6	0.0174	61.	0.0	247.0	-0.6	0.1
4	T	0	4	-0.1	0.3	0.4	-36.	3.	177.4	0.0217	-464.				0.6	0.0184	55.	3.9	247.4		
5	E	7	7	0.6	-0.1	0.6	2.	-9.	173.2	-0.0205	-486.	173.0	-0.0197	-506.	0.5	0.0124	40.	-3.5	243.1	0.1	-0.2
6	E	8	8	-0.1	-0.1	0.1	9.	6.	173.1	-0.0013	-501.	173.0	0.0000	-502.	0.5	0.0124	40.	-0.2	243.1	0.2	-0.1
7	T	0	9	-1.1	0.1	1.1	-3.	6.	173.2	0.0169	-495.				0.5	0.0124	40.	2.9	243.2		
8	E	14	13	-0.9	0.0	0.9	252.	-49.	169.3	0.0191	-464.	169.1	0.0184	-485.	0.5	0.0124	40.	3.2	239.2	-0.1	-0.2
10	E	0	14	0.7	-0.0	0.7	2.	-6.	169.1	0.0277	-497.				0.6	0.0174	61.	4.7	239.3		
11	E	15	15	0.3	0.0	0.3	3.	-7.	169.4	0.0477	-485.	169.2	0.0496	-505.	0.6	0.0188	63.	8.1	239.2	0.3	-0.2
14	E	0	18	-0.6	-0.1	0.6	6.	9.	165.0	-0.0034	-500.				0.6	0.0159	63.	-0.6	235.0		
15	E	19	19	-0.5	-0.1	0.5	4.	4.	165.0	0.0205	-507.	165.1	0.0217	-514.	0.6	0.0188	63.	3.4	235.0	0.2	0.1
16	E	5	5	0.5	-0.1	0.5	26.	-7.	177.2	0.0487	-515.	177.1	0.0475	-496.	0.5	0.0102	40.	8.6	247.0	-0.2	-0.1
17	E	0	6	-1.3	0.1	1.3	5.	16.	173.4	-0.0534	-489.				0.6	0.0190	75.	-9.3	243.2		
18	E	11	11	0.0	0.1	0.1	-4.	-7.	169.4	-0.0478	-488.	169.3	-0.0469	-496.	0.5	0.0102	40.	-8.1	239.2	0.2	-0.1
19	E	10	10	-0.3	0.0	0.3	3.	6.	173.3	0.0449	-494.	173.2	0.0442	-505.	0.5	0.0110	55.	7.8	243.3	-0.1	-0.1
21	T	16	16	-0.6	-0.0	0.6	8.	11.	165.0	-0.0581	-532.	165.3	-0.0518	-494.	0.7	0.0326	103.	-9.6	234.7	1.0	0.4
22	E	17	17	0.1	0.0	0.1	12.	-7.	165.2	-0.0278	-503.	165.1	-0.0222	-507.	0.5	0.0110	55.	-4.6	235.1	0.9	-0.0
24	T	12	12	-0.1	-0.1	0.1	4.	1.	169.4	-0.0192	-422.	169.0	-0.0255	-505.	0.5	0.0147	104.	-3.3	239.4	-1.0	-0.5
26	D	99	2	0.7	1.5	1.7	0.	0.	178.6	-0.0185	-509.				6.6	6.6469	80.	-3.3	248.6		
27	P	20	0	-0.7	0.1	0.7	0.	0.	0.0	0.0	-500.	165.3	0.0440	-500.	0.0	0.0	0.	0.0	0.0	0.0	0.0
28	P	21	0	0.0	0.0	0.0	0.	0.	0.0	0.0	-435.	164.8	-0.0412	-435.	0.0	0.0	0.	0.0	0.0	0.0	0.0

Fig.4 Scan-to-scan target and track data

TRACK/TARGET CORRELATION MATRIX FOR MONTE CARLO TRIAL *:

	TARGET NUMBERS																								
	REAL TARGETS																				FALSE REPORTS				
SCAN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	1	2	3	4	0	0	5	6	7	0	0	8	9	10	11	12	13	14	15	0	0	0	0	0	0
2	1	2	3	4	16	17	5	6	7	0	18	8	0	10	11	0	0	14	15	0	0	0	0	0	0
3	0	2	3	4	16	17	0	0	0	19	18	0	20	10	11	21	22	14	15	0	0	0	0	0	0
4	1	0	3	0	0	17	5	6	7	19	23	24	8	10	0	21	22	0	0	25	0	0	0	0	0
5	1	26	3	0	16	17	0	0	0	19	13	24	0	10	11	0	22	14	15	0	0	0	0	0	0
6	0	0	3	0	16	0	5	6	0	19	18	24	0	8	11	21	22	0	15	27	28	0	0	0	0
7	2	0	3	4	16	17	5	0	7	19	18	0	29	10	11	21	22	14	15	27	0	0	0	0	0
8	2	30	0	0	16	0	5	6	7	19	18	24	29	10	11	21	0	14	15	27	0	0	0	0	0
9	2	30	0	4	16	17	5	0	7	19	18	0	29	0	0	21	22	14	15	27	0	0	0	0	0
10	1	30	3	4	16	17	5	6	0	19	18	24	0	0	11	21	22	14	15	27	0	0	0	0	0
11	2	30	3	4	16	17	0	6	0	19	18	24	29	10	11	21	22	14	15	27	0	0	0	0	0
12	0	30	3	0	16	0	5	6	7	19	18	24	29	10	11	21	0	14	15	0	0	0	0	0	0
13	1	30	3	0	16	17	0	0	7	19	18	0	29	10	11	21	22	14	15	27	0	0	0	0	0
14	1	30	0	4	16	17	0	6	7	19	18	24	0	10	11	21	0	0	15	0	0	0	0	0	0
15	1	30	3	4	0	17	0	6	0	0	18	24	29	10	11	21	22	14	15	0	0	0	0	0	0
16	1	30	0	4	16	17	5	6	7	19	16	24	29	10	11	21	0	14	15	27	0	0	0	0	0
17	1	30	3	4	16	17	5	6	7	19	18	0	29	10	11	21	22	14	15	27	0	0	0	0	0
18	1	30	3	4	0	17	0	6	7	19	18	24	29	0	11	21	22	14	15	0	0	0	0	0	0
19	1	30	3	4	0	17	5	6	0	0	0	24	29	10	0	21	22	14	15	27	0	0	0	0	0
20	1	30	3	4	16	0	5	6	0	19	18	24	29	10	11	0	22	14	15	27	0	0	0	0	0
21	0	30	3	4	16	17	0	6	0	19	18	24	29	0	11	21	22	14	15	27	0	0	0	0	0
22	1	30	3	4	16	17	5	6	7	0	18	24	29	10	11	21	22	14	15	27	0	0	0	0	0
23	1	0	0	4	16	0	5	6	7	19	18	24	29	10	0	0	22	14	15	27	0	0	0	0	0
24	1	0	0	0	16	17	5	6	0	19	18	24	29	0	0	21	22	14	15	0	0	0	0	0	0
25	0	30	3	4	0	17	5	6	0	0	0	0	29	10	11	21	22	0	15	27	0	0	0	0	0
26	1	0	3	4	16	17	0	6	7	19	18	24	0	10	11	21	22	14	0	27	0	0	0	0	0
27	1	30	0	4	16	17	0	6	7	19	18	24	29	10	11	21	0	14	15	27	0	0	0	0	0
28	0	30	3	4	16	17	0	6	7	19	18	24	29	0	11	21	22	14	15	0	0	0	0	0	0
29	1	30	3	4	16	0	0	6	7	19	18	0	29	10	11	21	22	14	15	27	0	0	0	0	0
30	0	30	3	0	16	17	5	6	7	19	18	24	29	10	0	21	22	14	0	27	0	0	0	0	0

Fig.5 Track/target correlation matrix

SCAN BY SCAN HISTORY FOR TRACK NUMBER 2

1-SCAN NO. 2-TRACK STATUS 3-UPDATE TARGET NO. 4-TRACK X ERROR 5-TRACK Y ERROR 6-TRACK POSITION ERROR 7-TRACK SPEED ERROR 8-TRK HEADING ERROR 9-PREDICTED RANGE 10-PREDICTED AZIMUTH 11-PREDICTED RANGE RATE 12-RANGE GATE 13-AZIMUTH GATE 14-RANGE RATE GATE

1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	P	2	0.7	0.1	0.8	0.	0.	0.0	0.0	-493.	0.0	0.0	0.
2	T	2	-0.2	0.1	0.2	93.	35.	180.1	-0.0181	-507.	6.7	6.6515	80.
3	T	2	-1.0	0.0	1.0	98.	31.	178.5	-0.0287	-477.	0.5	0.0147	103.
4	T	0	-1.8	-0.0	1.8	98.	31.	177.9	-0.0327	-505.	0.5	0.0110	54.
5	T	0	-2.7	-0.1	2.7	98.	31.	177.5	-0.0376	-504.	0.5	0.0146	54.
6	T	0	-3.5	-0.1	3.5	98.	31.	177.1	-0.0424	-502.	0.6	0.0185	54.
7	E	1	0.0	0.1	0.1	68.	29.	176.7	-0.0473	-506.	0.7	0.0225	54.
8	E	1	-0.4	0.1	0.4	60.	27.	176.6	-0.0494	-482.	0.6	0.0184	51.
9	E	1	-0.6	0.1	0.6	48.	25.	176.2	-0.0516	-485.	0.5	0.0161	46.
10	E	0	-1.2	0.1	1.2	45.	25.	175.9	-0.0526	-466.	0.5	0.0152	44.
11	E	1	-1.4	0.1	1.4	38.	22.	175.5	-0.0563	-485.	0.5	0.0161	44.
12	E	0	-2.0	0.1	2.0	38.	22.	175.2	-0.0569	-485.	0.5	0.0151	43.
13	E	0	-2.5	0.2	2.5	38.	22.	174.8	-0.0603	-484.	0.5	0.0158	43.
14	E	0	-3.1	0.2	3.1	38.	22.	174.5	-0.0636	-483.	0.5	0.0166	43.
15	E	0	-3.7	0.2	3.7	38.	22.	174.1	-0.0670	-483.	0.6	0.0175	43.
16	E	0	-4.2	0.2	4.2	38.	22.	173.8	-0.0705	-482.	0.6	0.0184	43.
17	E	0	-4.8	0.2	4.8	38.	22.	173.4	-0.0739	-481.	0.6	0.0194	43.
18	E	0	-5.4	0.2	5.4	38.	22.	173.1	-0.0773	-480.	0.6	0.0191	43.
19	E	0	-5.9	0.2	5.9	38.	22.	172.8	-0.0808	-479.	0.7	0.0191	43.
20	E	0	-6.5	0.2	6.5	38.	22.	172.4	-0.0853	-478.	0.7	0.0191	42.
21	E	0	-7.1	0.2	7.1	38.	22.	172.1	-0.0877	-478.	0.7	0.0192	42.
22	E	0	-7.6	0.2	7.7	38.	22.	171.8	-0.0912	-477.	0.8	0.0192	42.
23	E	0	-8.2	0.2	8.2	38.	22.	171.4	-0.0947	-476.	0.8	0.0192	42.
24	E	0	-8.8	0.2	8.8	38.	22.	171.1	-0.0983	-475.	0.8	0.0193	42.
25	E	0	-9.4	0.2	9.4	38.	22.	170.8	-0.1018	-474.	0.9	0.0193	42.
26	E	0	-9.9	0.2	9.9	38.	22.	170.5	-0.1053	-473.	0.9	0.0194	42.
27	E	0	-10.5	0.3	10.5	38.	22.	170.2	-0.1089	-472.	0.9	0.0194	42.
28	E	0	-11.1	0.3	11.1	38.	22.	169.8	-0.1125	-471.	0.9	0.0194	42.
29	E	0	-11.6	0.3	11.6	38.	22.	169.5	-0.1161	-470.	1.0	0.0195	42.
30	E	0	-12.2	0.3	12.2	38.	22.	169.2	-0.1197	-469.	1.0	0.0195	42.

Fig.6 Track history

MONTE CARLO TRIAL 0 SUMMARY STATISTICS:

NUMBER OF ESTABLISHED TRACKS	22	NUMBER OF VALID TRACKS	20
NUMBER OF LOST TRACKS (>0)	0	NUMBER OF LOST TRACKS (>1)	0
NUMBER OF FALSE TRACKS	2	NUMBER OF DISOWNED TRACKS	0
NUMBER OF TRACK ATTEMPTS	30	AVG SCAN OF PROMOTION TO EST	6.45
NUMBER OF TARGETS INITIATED	20	AVG SCAN OF 1ST VALID PROMOTION	6.45
# TGTS INIT WITHIN 10 SCANS	20	MAXIMUM NUMBER OF TRACKS	22

Fig.7 ATI performance summary

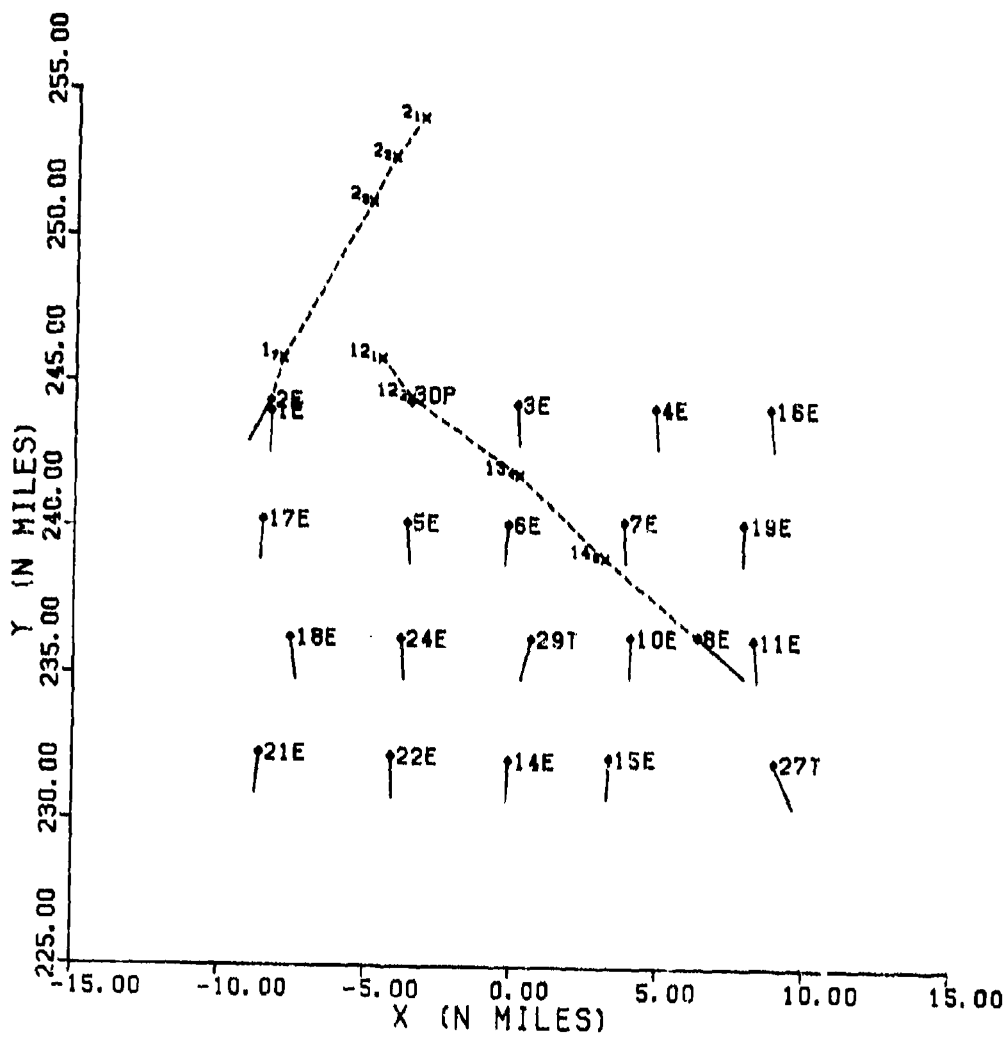


Fig.8 Track/Target plot output

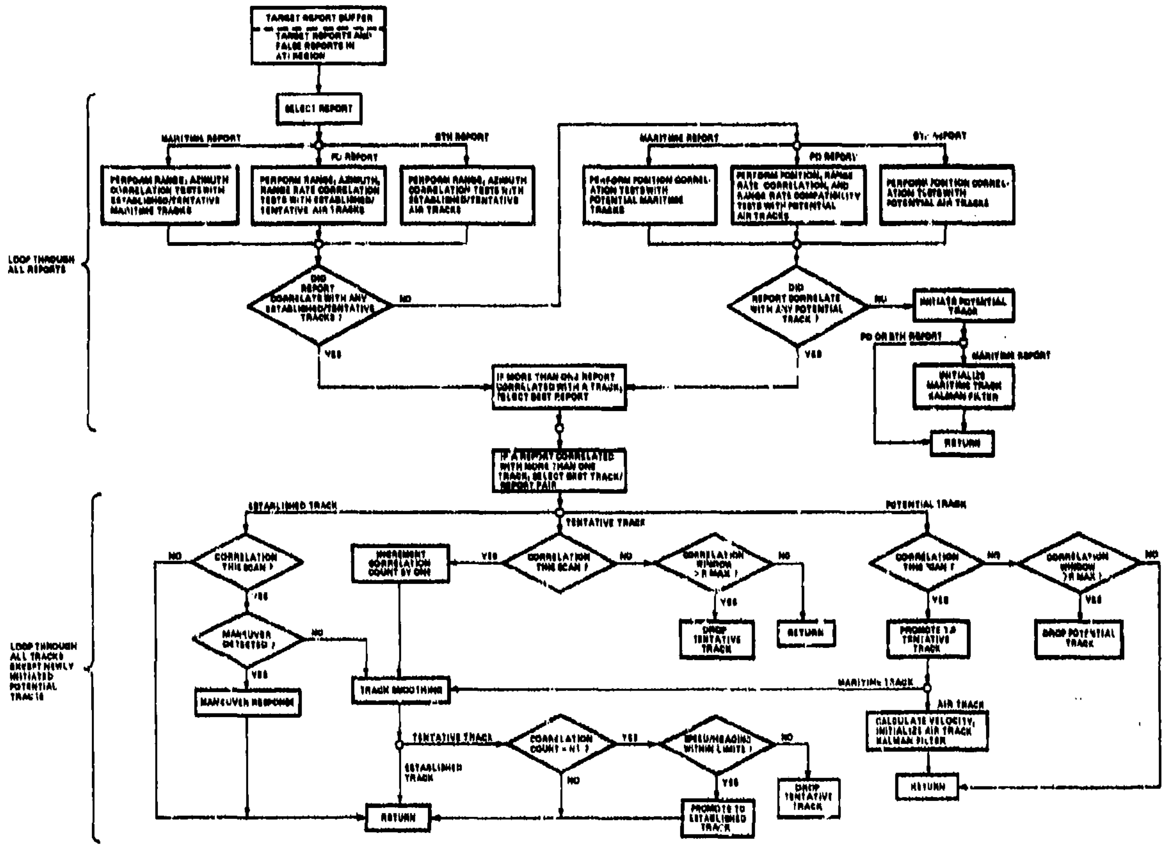


Fig.9 ATI/tracker flowchart

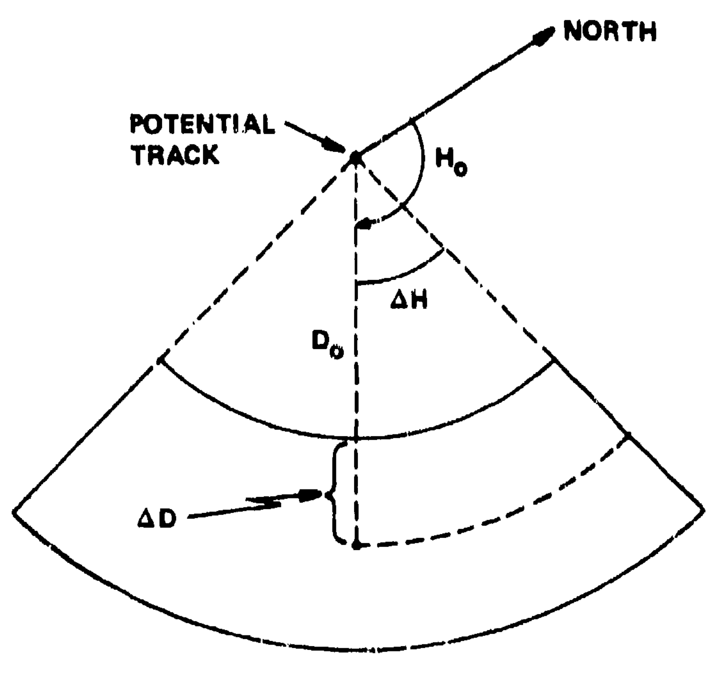


Fig.10 Potential air track correlation window

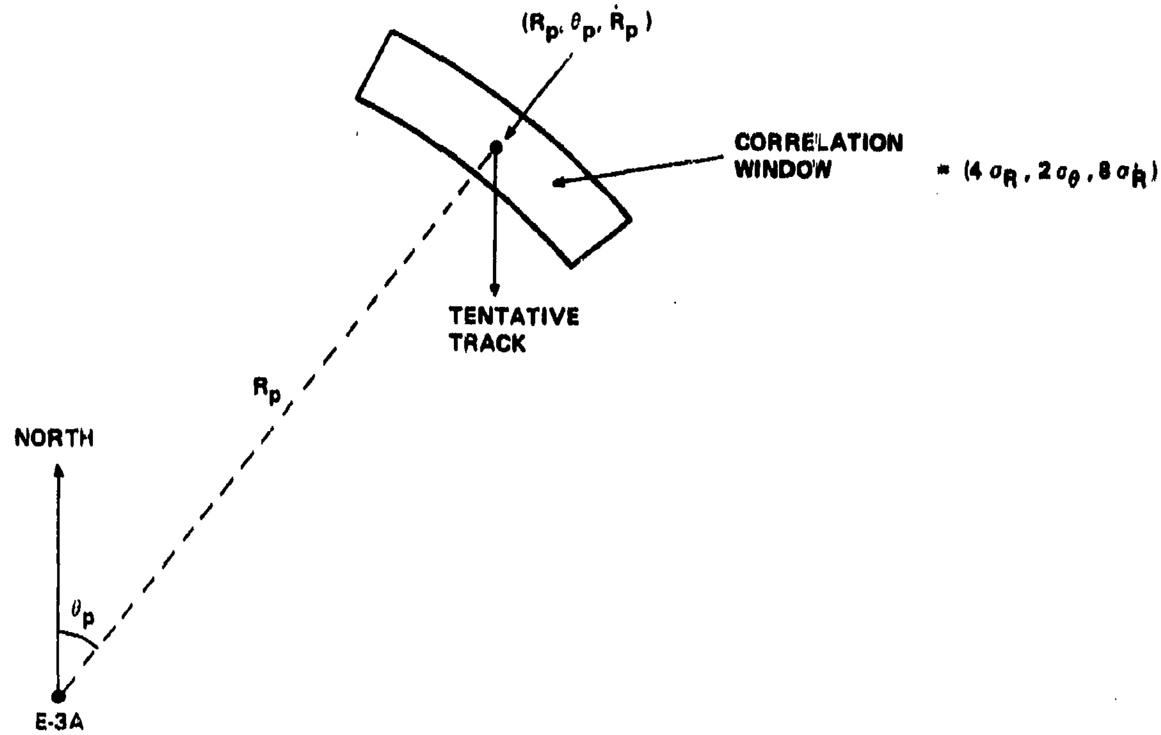


Fig.11 Tentative air track correlation window

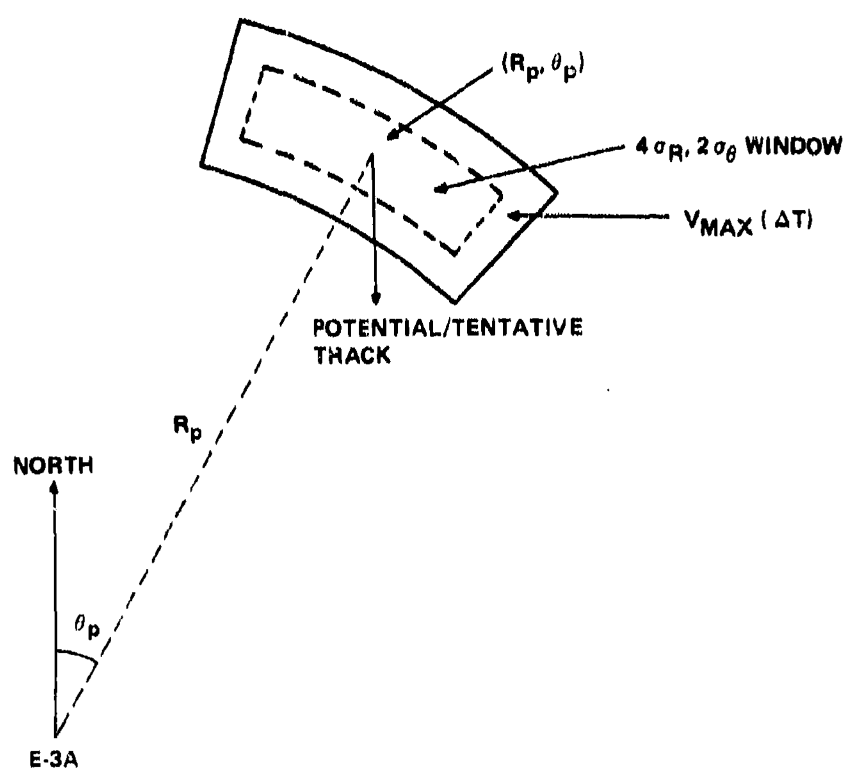


Fig.12 Potential/tentative maritime track correlation window

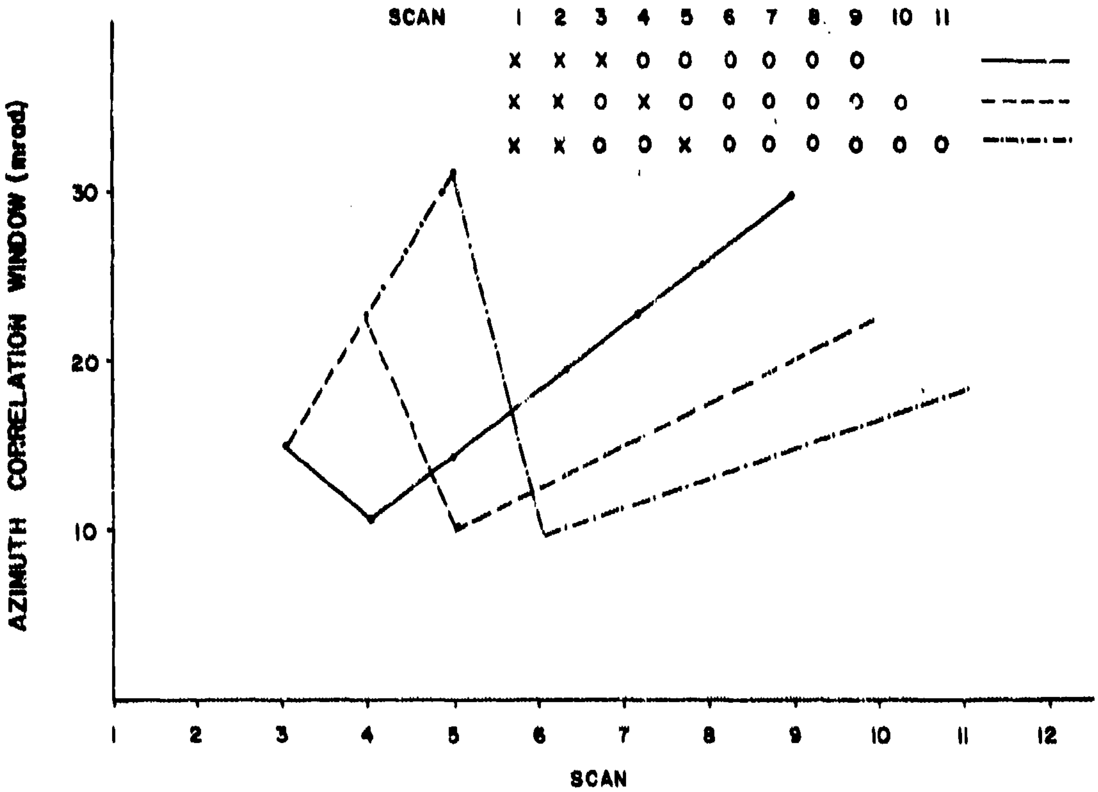


Fig.13 Azimuth correlation window (2/2 to tentative)

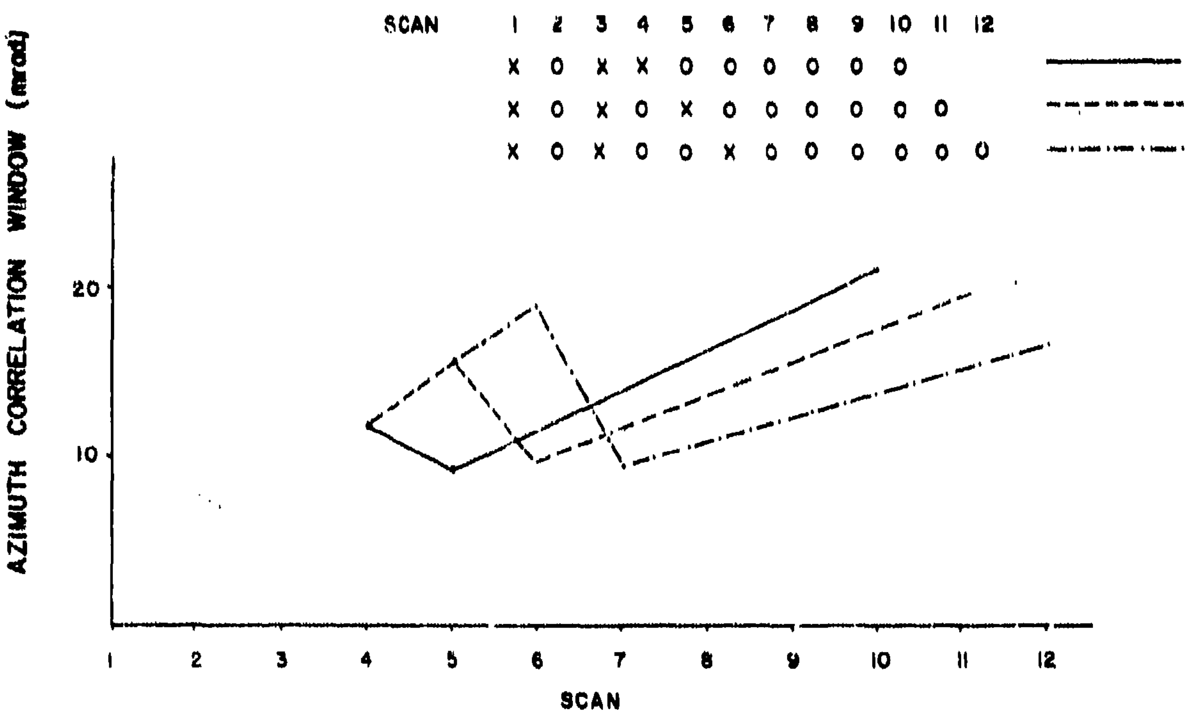


Fig.14 Azimuth correlation window (2/3 to tentative)

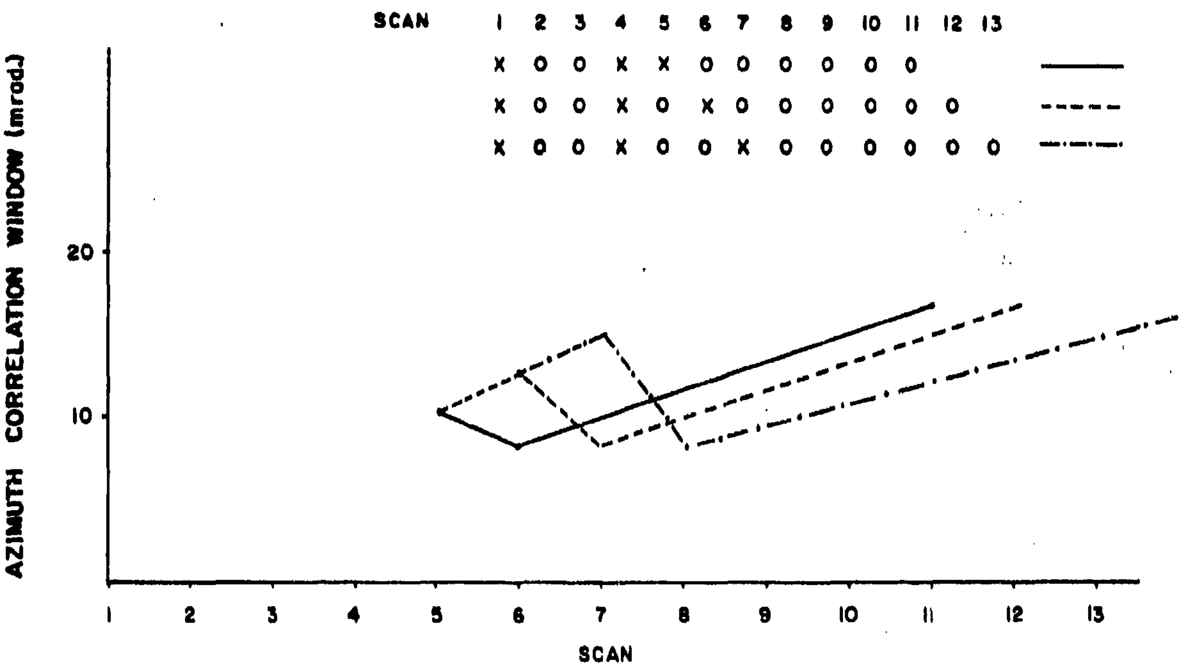


Fig.15 Azimuth correlation window (2/4 to tentative)

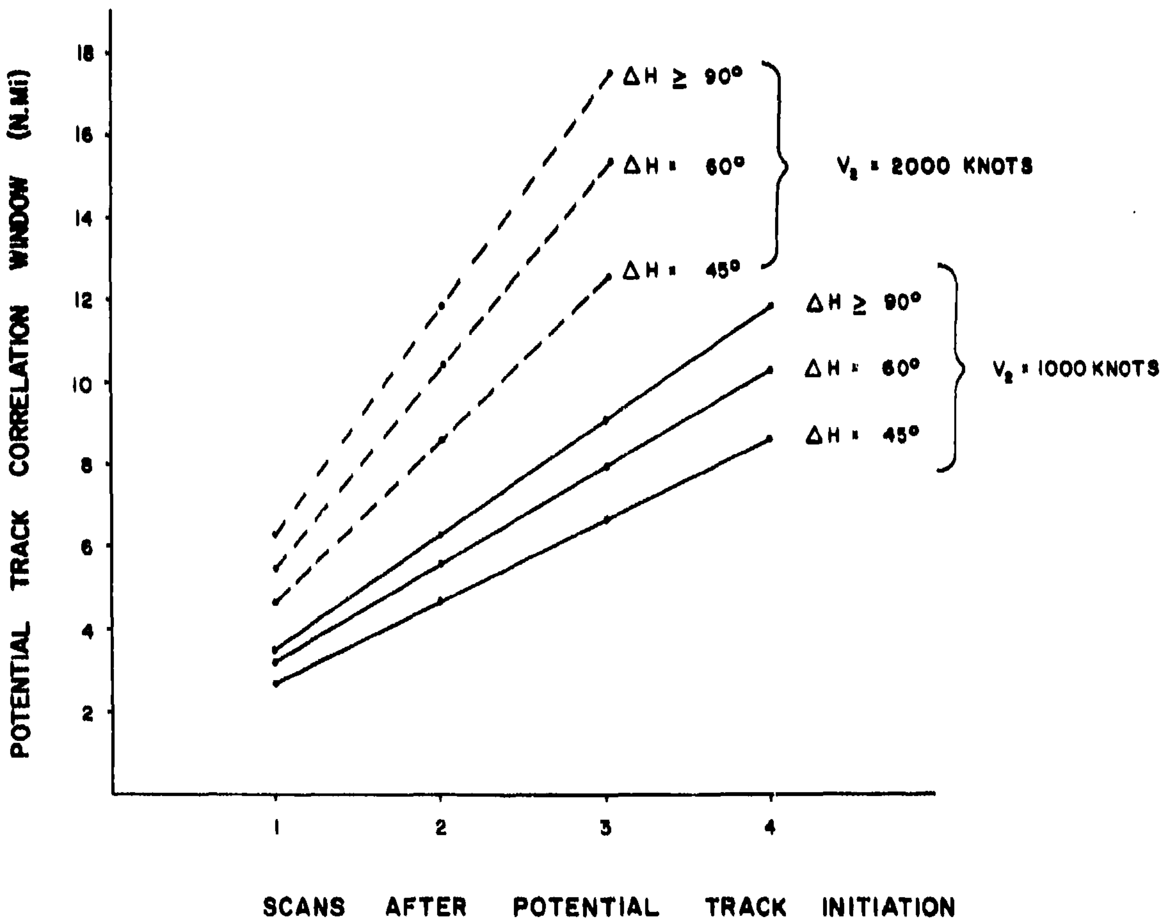


Fig.16 Potential track correlation window sizes

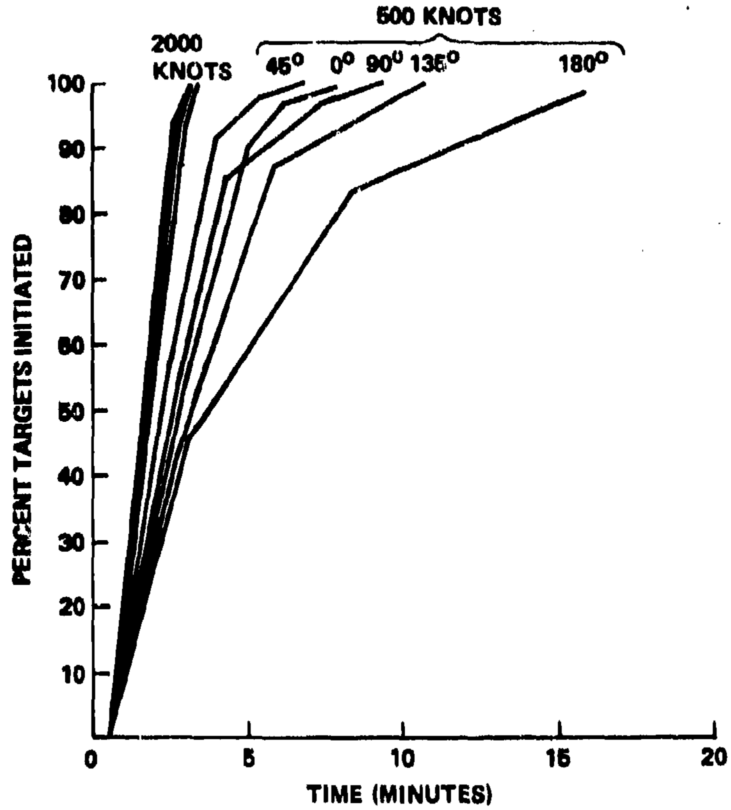


Fig.17 ATI performance (air targets)

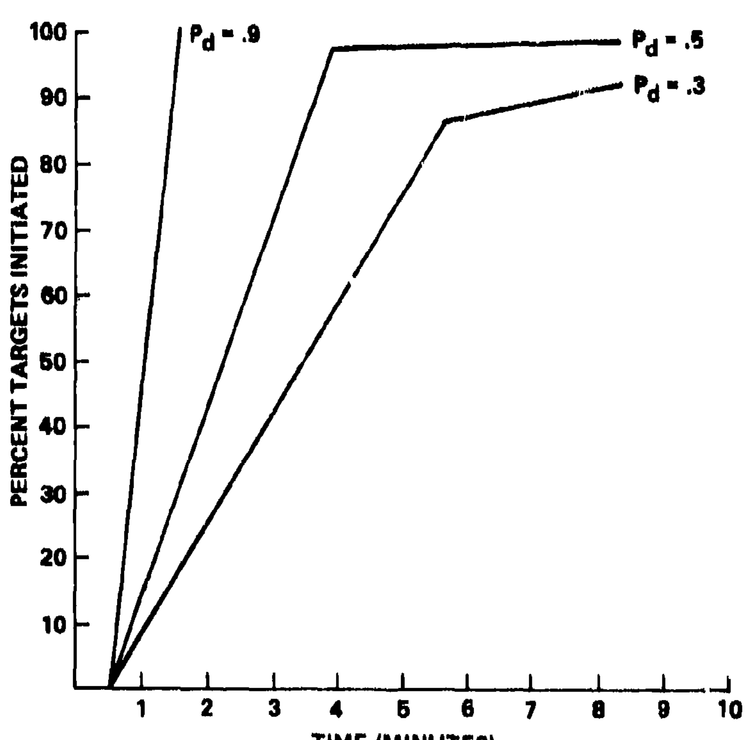


Fig.18 ATI performance (maritime targets)

AVIATION TRAINING USING VIDEO DISK TECHNOLOGY

Craig Fields
Defense Advanced Research Projects Agency
Arlington, Virginia USA

Steven Levin
Interactive Television Company
Arlington, Virginia USA

ABSTRACT

Video disks are a new technology that provide inexpensive storage (65¢/disk) and rapid access (as little as 1/8 sec.) to large numbers (54,000 pictures/disk side) of photographs. For a typical airport, it is possible to store on a video disk compressed movies showing all runway, take-off, landing, circling, and approach paths. When such a disk is viewed on a player and television controlled by a simple microprocessor, the pilot can vicariously fly himself around an airport, land, take-off, taxi and circle. The pilot sees an image with photographic realism, can choose his own path and speed, and can choose time of day or weather conditions for the simulated trip. Such a system is one hundred times less expensive than a conventional flight simulator.

1. INTRODUCTION

Video disk-based flight trainers were developed to provide the student with vicarious flight experience and knowledge of the characteristics of particular airports. The technology has advantages over movies of flight and of airports in that the student can choose his path and line of sight. The technology also has advantages over conventional flight simulators in that the imagery has photographic realism, no costly digital data base of the airport and terrain needs to be developed, and the hardware and software of the video disk-based flight trainer is vastly less expensive than current color three dimensional display processors.

2. BACKGROUND

Video disks are similar to audio records, except that they store pictures instead of sound. Each of the two sides of a twelve inch diameter video disk can store thirty minutes of television, the equivalent of 54,000 still pictures (30 minutes x 60 seconds/minute x 30 frames/second). A video disk player can show the video disk as a movie, including capabilities for slow motion forward and backward, scanning forward and backward, and stopping on a single frame. With the current technology in the marketplace, the surface of the video disk is read by measuring the reflectance of a laser, and so the disk never wears out due to physical wear. In addition, the video disk player can randomly access any of the 54,000 frames on the video disk in a maximum of three seconds and a minimum of about 1/8 second because each frame is digitally coded with a frame number, even though the picture itself is an analog signal. The frame to be found is defined by keying a frame number into a control on the video disk player, or can be defined by sending digital signals to a standard electrical connector on the video disk player.

Video disks can be made in a number of ways. We begin with a 16mm film that should be considered a sequence of still frames rather than a movie. In addition, 35mm film or video tape can be used as the original material. If film is used, it is converted to video tape. The final video signal is used to produce a master video disk, and this master in turn is used as a stamper to produce video disks in much the same way that audio disks are produced. Consequently, video disks cannot be changed unless the original material is edited, followed by the production of a master and new video disks.

When video disk players are controlled by a computer, the combination can be used to provide a viewer with a personalized movie. A number of viewing options are stored on the video disk, and with the aid of the computer to locate particular movie segments, the user chooses among options to see what he wants. Because of the rapid random search capability of the video disk player, an essentially continuous movie can be displayed.

The problem with this approach to personalized movies is that the total capacity of the video disk, thirty minutes on a side, does not allow for a large number of viewing options. If, for example, the video disk contained ten viewing options, the user might choose a personalized movie only three minutes long.

One potential solution is to store and display fewer than thirty frames/second for movie viewing. For some subject matter, such as very slow motion, many fewer than thirty frames/second can be employed and the resulting display still appears to be of continuous motion. For other action, such as the view out of an airplane, displaying many fewer than thirty frames/second produces the appearance of discontinuous motion. Fortunately, in this case the discontinuous motion is not burdensome for the viewer and provides the advantage of allowing the storage of hours of flight on a video disk and the storage of a number of flight options.

3. APPROACH

We have produced a flight trainer for travel on and around a small, rural airport - Frederick, Maryland, US. We filmed views from the cockpit of an airplane facing forward, to the right, and to the left. Simultaneously, we filmed selected instruments on the instrument panel. Frames were photographed every half second. Film was collected while the plane performed the following movements: take-off and landing from each of the four runways, including travel to and from the apron; circling at a radius of one half mile and a radius of one mile, at altitudes of 1100 feet and 2500 feet; and transitions among the circlings, take-offs and landings.

A video disk was produced, and a digital index was prepared that listed the location on the video disk (frame numbers) of each segment of plane travel. Software in a microcomputer connected to the video disk player controlled the display of flight options and viewpoints, based on commands delivered to the microprocessor by the user using a joystick and function button controls that did not attempt to simulate realistic flight controls.

4. DISCUSSION

Movies are typically used to familiarize students with particular airports. The video disk-based flight trainer performs this function, and gives the additional advantage of allowing the student to control his flight or taxi path, his viewpoint, and his speed. The flight trainer is more expensive than movie projection equipment, and evaluation is needed to determine whether it is more cost-effective. An important part of the calculation is that the flight trainer is apparently more attractive and "fun" to use than passive viewing of a movie, and hence may lead to better learning, and more viewing and practice.

Flight simulators can substitute for some in-flight training in an effort to reduce training costs. Unfortunately, the display processors of flight simulators are quite expensive, and the construction of a digital data base for an airport or other area is a major undertaking. At best, the display appears cartoon-like. With the inexpensive flight trainer the display has photographic realism, no digital data base describing the terrain and cultural features is needed, and an expensive display processor is eliminated. Unfortunately, with the flight trainer the student can choose among a modest number of prerecorded paths and views, e.g. fifty to one hundred options. With a flight simulator the student can choose among an essentially infinite number of flight paths, including crashing, and hence experiences more realistic dynamics, if less realistic displays. Hence the device described in the paper is termed a flight <u>trainer</u> rather than a flight <u>simulator</u>. Evaluation is needed to determine whether a flight trainer using video disk technology is more or less cost-effective than a traditional flight simulator.

CONCEPTION D'UN SIMULATEUR DE VOL D'ETUDE POUR HELICOPTERE - S D V E H -

JL. MASCLE - G. CATANI - M. SELLIER* - JP. LETOUZEY

Service Etudes Systèmes Avancés
*Service Informatique
Bureau d'Etude de la SNIAS -
Division Hélicoptères MARIGNANE - FRANCE

- R E S U M E -

Cet exposé traite de la conception d'un simulateur de vol d'étude adapté aux problèmes spécifiques des hélicoptères militaires pour la définition et mise au point d'uneavionique moderne.

Il montre comment le besoin exact a été défini, en particulier dans le cadre du développement d'un nouveau programme hélicoptère.

Les principales caractéristiques d'un tel simulateur sont présentées ainsi qu'une liste des points jugés critiques pour ce projet - Sommaire : 1. Introduction - 2. Analyse préliminaire du besoin SDVEH - 3. Contraintes du projet - 4. Organisation générale et programme de développement - 5. Points critiques - 6. Conclusion.

1. INTRODUCTION

Dans le domaine des Hélicoptères Militaires, l'importance de l'avionique par rapport à la motorisation et au véhicule croît rapidement. Ceci peut s'expliquer par :

A. Le désir des Opérationnels d'étendre le champ d'application des Hélicoptères de deux façons différentes.

Tout d'abord, il est demandé de pouvoir remplir des missions nouvelles d'appui anti-personnel, d'escorte et de lutte air-air anti-hélicoptère nécessitant la mise en oeuvre de systèmes d'arme plus complexes.

D'autre part, il est demandé de pouvoir remplir certaines missions de jour comme de nuit et dans certains cas de mauvaise visibilité, ce qui nécessite le plus souvent, la mise en oeuvre de moyens optroniques sophistiqués.

B. La nécessité de maintenir l'efficacité opérationnelle des Hélicoptères dans l'avenir en revalorisant leurs systèmes d'arme.

Les progrès réalisés en matière de "guerre électronique" impliquent dès maintenant de prévoir des moyens embarqués de Contre-Mesures Electroniques. Par ailleurs, de nouveaux types d'intervention

basés sur les actions combinées, (exemple : les désignations de cibles à l'aide de moyens d'illumination et de détection laser) impliquent la mise en oeuvre d'une avionique complexe.

Enfin, l'avènement des commandes électriques laisse entrevoir de nouvelles possibilités prometteuses en matière de pilotage.

Cette importance croissante de l'avionique en rend la conception et la mise au point plus complexes et plus longues.

Dans le cadre d'un nouveau programme, il devient impératif de lancer des études très complètes de l'avionique, dès le début du programme afin de respecter les délais de développement et d'éviter des modifications tardives de l'avionique qui risquent d'être coûteuses et de dégrader l'efficacité opérationnelle.

En effet, la complexité d'une avionique moderne en rend toute modification très délicate, à mesure que l'on progresse dans sa définition, en particulier une fois que l'on a atteint le stade des essais en vol d'un prototype.

Par ailleurs, les interactions entre la cellule, la motorisation et l'avionique sont de plus en plus importantes : il devient nécessaire de conduire le développement des trois entités conjointement au niveau des études de façon à assurer une intégration réussie.

Un simulateur sol permettant entre autre d'analyser le comportement en vol d'un équipage d'hélicoptère au cours d'une mission est l'un des moyens d'étude adapté pour résoudre ces difficultés.

L'expérience montre en outre qu'un simulateur adaptable aux problèmes posés est un moyen rentable efficace et parfois unique de mener certaines études (exemple : la mise au point d'un système d'arme dans différentes configurations de combat difficiles à obtenir en conditions réelles d'essai ou l'analyse de la charge de travail).

L'objet de ce document est de présenter un projet de développement d'un simulateur d'étude conçu dans cet esprit.

Ce projet s'appelle Simulateur De Vol d'Etude pour Hélicoptère.

2. ANALYSE PRELIMINAIRE DU BESOIN SDVEH

2.1. APPROCHE DU BESOIN

Initialement, le SDVEH était défini comme une installation capable de simuler en temps réel le vol d'un hélicoptère intégrant la participation effective d'un équipage.

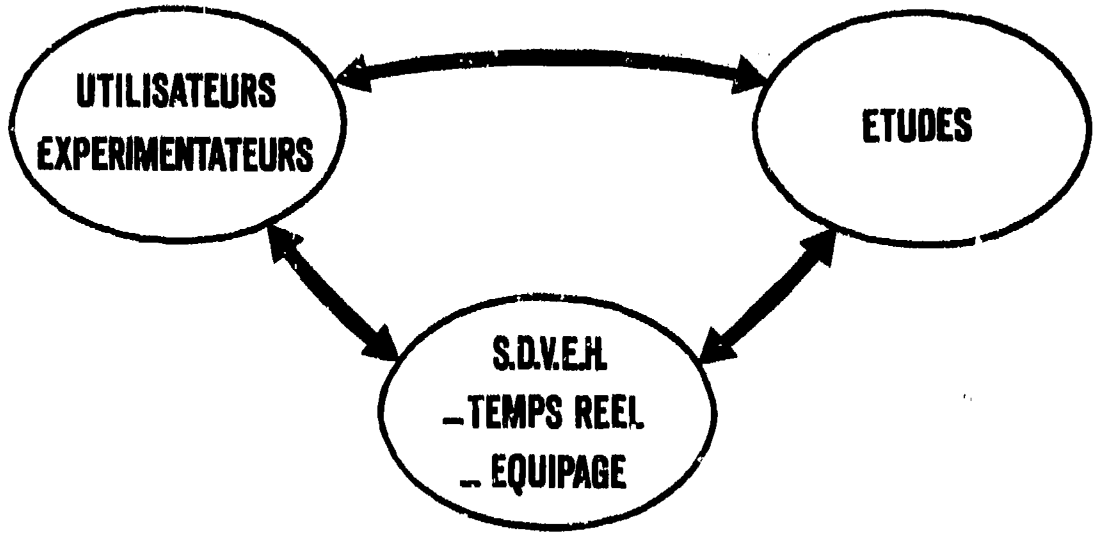
Il était nécessaire de préciser cette définition avant d'entreprendre toute réalisation.

La complexité du sujet nous a conduit à adopter une approche selon trois grands principes.

A. Le SDVEH doit être considéré comme un tout :

C'est-à-dire ne pas décomposer à priori le SDVEH en sous-ensembles indépendants pouvant faire l'objet de définitions indépendantes, ou définir le SDVEH en négligeant certains de ces aspects comme celui de sa mise en oeuvre par ses futurs utilisateurs au profit de celui de ces objectifs d'étude.

Le schéma suivant illustre cette attitude de départ.



B. Le SDVEH doit être resitué dans son contexte général :

C'est-à-dire analyser l'environnement d'étude dans lequel s'inscrit le SDVEH afin d'en préciser tous les aspects et fixer des objectifs concrets, échelonnés dans le temps.

L'analyse des points suivants est essentielle.

- objectifs d'études } préciser s'il s'agit de court, moyen ou long terme
- objectifs de mise en oeuvre }
- complémentarité du SDVEH par rapport aux autres moyens d'étude.

C. Le SDVEH doit être compris pour sa réalisation comme un ensemble d'éléments en interaction doté d'une organisation

Il convient d'établir le schéma fonctionnel et organique du SDVEH précisant les différents sous-ensembles, les relations internes qui existent entre eux ainsi que les relations externes avec des ensembles ne faisant pas partie du SDVEH mais en interaction avec ce dernier.

Le travail a été amorcé en définissant et analysant d'une part les objectifs d'étude du simulateur et d'autre part, les objectifs pour sa mise en oeuvre par ses utilisateurs futurs.

2.1.1. Objectifs d'étude

Objectifs généraux

Les objectifs d'étude ont d'abord été définis d'un point de vue général, en considérant les différentes phases caractéristiques du développement d'un nouveau programme hélicoptère et pour chacune d'elle, la façon dont le SDVEH pouvait intervenir en insistant sur les points suivants :

- position du SDVEH par rapport aux autres moyens d'étude disponibles dans cette phase
- stade de développement de la machine et de l'avionique dans cette phase.

La Planche 1 résume les objectifs généraux d'étude retenus.

On a en particulier mis en évidence que la conception et mise au point de l'avionique d'un nouveau programme induit des études qui peuvent déborder de leur cadre habituel correspondant aux phases de faisabilité et de définition, et qui constituent des applications possibles du SDVEH.

Ceci répond en particulier à la difficulté de mise au point des symbologies ou à l'impossibilité de reconnaître certains problèmes avant de disposer d'une avionique complètement définie ainsi qu'au caractère évolutif des systèmes d'arme modernes.

Objectifs d'études spécifiques

Des objectifs d'études spécifiques ont été dégagés à partir des objectifs généraux en considérant des programmes ou projets particuliers en cours ou à venir.

Chaque étude retenue a été définie dans la mesure du possible par ses objectifs exacts, la date à laquelle elle doit être menée et la phase correspondante du programme dont elle est issue. De plus, on s'est attaché à la définition de ce qu'il était important de simuler pour valider les résultats de l'étude.

2.1.2. Objectifs de mise en oeuvre

Les objectifs d'études ont été complétés par des objectifs de mise en oeuvre.

- Le SDVEH doit être un moyen d'étude rentable, c'est-à-dire qu'il ne doit pas être plus onéreux que les autres moyens d'étude disponibles pour un travail identique.
- L'effort de développement et de mise au point des logiciels - exemple le modèle de mécanique du vol - doit s'inscrire dans un contexte plus global que leur seule utilisation pour le SDVEH.
- Le SDVEH doit offrir une bonne disponibilité et être d'un emploi facile pour ses utilisateurs potentiels sans l'aide d'une formation spécialisée.

2.2. DEFINITION CONCEPTUELLE DU SDVEH

Les résultats de cette approche conduisent à la définition conceptuelle suivante.

"Un simulateur de vol d'étude pour hélicoptère est un moyen d'étude capable de restituer en temps réel, le vol vu et senti par l'équipage d'un hélicoptère dans son environnement et avec tous les moyens d'aide au pilotage qui sont à sa disposition".

Par rapport à la définition initiale, qui met l'accent sur le fonctionnement temps réel et la présence d'un équipage, on voit apparaître ici les notions complémentaires de "vol vu et senti", "d'environnement", "de moyens d'aide au pilotage" et de "moyen d'étude".

Les notions de "vol vu et senti" et "d'environnement" traduisent le rôle déterminant, dans le comportement d'un équipage d'hélicoptère, particulièrement en vol tactique, d'informations directes issues de la vision du monde extérieur et de sensations diverses de vibrations ou accélérations.

En effet, le vol tactique tel que le pratique l'Armée de Terre Française, consiste à voler au plus près du sol (hauteur de vol de quelques mètres ou dizaines de mètres au maximum) en exploitant le relief et la végétation pour échapper aux moyens de détection ennemis. Au cours d'un tel vol, les obstacles à éviter sont nombreux et variés (arbres, câbles, pylônes, falaise, etc ...)

Le seul moyen de surmonter toutes ces difficultés pour l'équipage, consiste actuellement à observer constamment l'environnement extérieur, pour définir et contrôler une trajectoire de vol entre les obstacles.

La simulation d'une telle vision de l'environnement extérieur pose de nombreux problèmes et différencie radicalement un simulateur Hélicoptère d'un simulateur Avion.

Par ailleurs, il importe pour le SDVEH de ne pas négliger, à priori, des informations qui peuvent se révéler décisives dans le comportement de l'équipage à l'occasion de certaines études et donc indispensables pour valider les résultats.

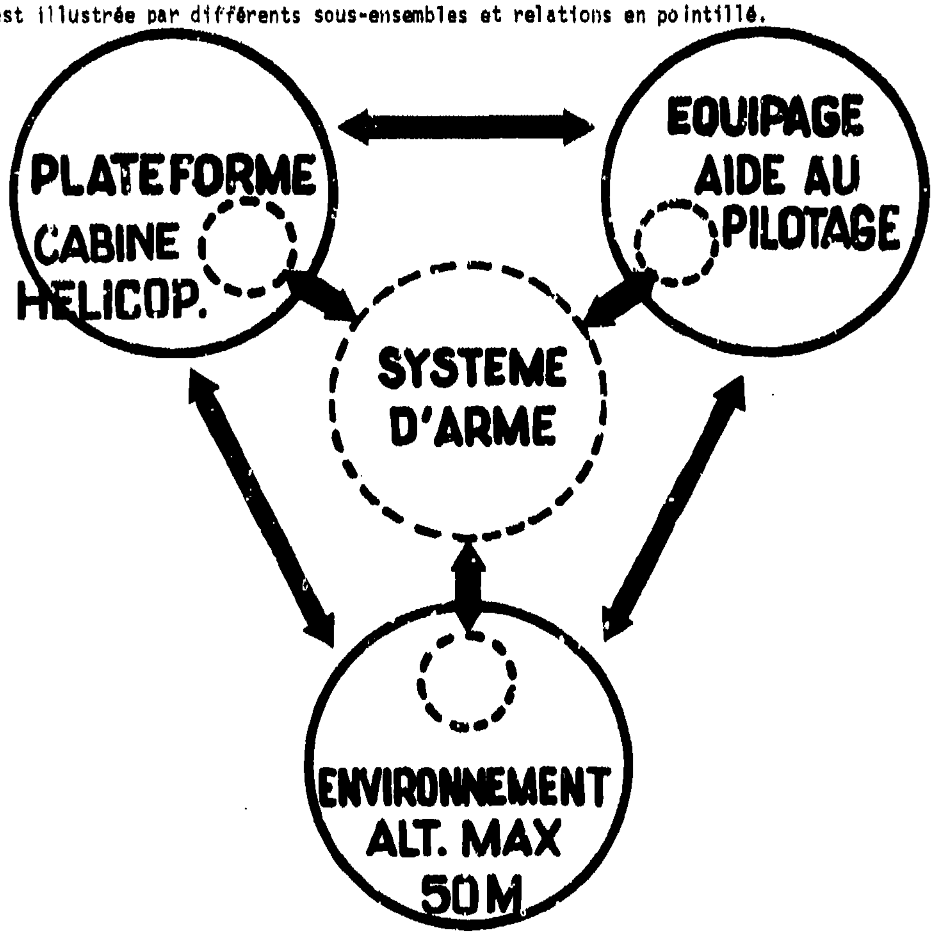
Cette remarque établit la différence qui existe entre un simulateur d'étude et un simulateur d'entraînement qui vise à entretenir ou développer une aptitude pour laquelle certaines "simplifications" sont admissibles.

La notion "de moyens d'aide au pilotage" traduit la nécessité de replacer l'équipage dans un environnement cabine très proche de la réalité pour l'analyse du comportement de l'équipage dans la satisfaction de certaines fonctions, en particulier le pilotage.

En outre, la notion "d'équipage" est maintenue car actuellement aucune mission hélicoptère n'est envisagée sans une étroite collaboration de deux équipiers au moins.

La notion de "moyen d'étude" traduit la nécessité pour le SDVEH d'avoir un caractère pluraliste dans ses applications et d'être capable, en particulier, d'une intégration potentielle à un système d'arme en prévoyant diverses relations et la présence de fonctions spécifiques.

Le schéma suivant résume la définition établie. L'intégration potentielle d'un système d'arme est illustrée par différents sous-ensembles et relations en pointillé.



2.3. SPECIFICATIONS MISE EN OEUVRE

De plus, des spécifications de mise en oeuvre ont été retenues :

- Le simulateur doit offrir une bonne fiabilité et maintenabilité
- Les moyens de dialogue entre le SDVEH et son utilisateur doivent être souples, variés et banalisés. La programmation se fera dans un langage de haut niveau
- Le Logiciel doit être utilisable pour d'autres applications temps réel ou non
- L'organisation du simulateur doit être modulaire.

3. CONTRAINTES DU PROJET

La réalisation d'un projet est toujours soumise à des contraintes extérieures. Pour le SDVEH, trois contraintes majeures ont été prises en compte :

- Concevoir un plan de développement du SDVEH qui permette de l'utiliser à court terme dans le cadre de programmes ou projets en cours
- Limiter les coûts de développement du SDVEH en exploitant en priorité les moyens matériels de simulation du Centre d'Essais en Vol d'Istres
- Choisir des moyens matériels qui s'harmonisent parfaitement avec ceux des différents utilisateurs potentiels.

  Ceci influe en particulier sur l'architecture générale du simulateur et sur le choix des moyens informatiques, périphériques associés et diverses interfaces.

4. ORGANISATION GENERALE ET PROGRAMME DE DEVELOPPEMENT

4.1. ORGANISATION FONCTIONNELLE ET ORGANIQUE

Les conclusions de l'analyse préliminaire et des contraintes exposées permettent de définir une première organisation fonctionnelle et organique du SDVEH. (Voir schéma Planche 2) installée au Centre d'Essais en Vol d'Istres.

Sur le plan organique, on distingue quatre sous-ensembles principaux :

- la cabi[illegible]t tous les instruments d'interface des postes d'équipage,
- l'unité informatique,
- le système de restitution de la vision du monde extérieur,
- la plateforme de mise en mouvement de la cabine.

- La plateforme de mise en mouvement de la cabine doit participer à la restitution d'une ambiance de vol aussi proche que possible de celle d'un vol réel, en simulant, en particulier des sensations d'accélération.

  La plateforme choisie est une plateforme LMT à 6 degrés de liberté. Son mouvement est du type araignée à 6 vérins. Les débattements maximaux sont de ± 1,6 m. Elle peut supporter une charge de 10 tonnes et recevoir une sphère de visualisation.

- La cabine, quant à l'organisation des postes d'équipage, est le résultat d'un maquettage dynamique poussé : elle est la réplique exacte d'une cabine d'hélicoptère, équipée d'instruments et commandes d'interface réels ou non, capables d'un fonctionnement simulé. Elle permet des réorganisations des postes d'équipage à l'occasion de différentes études.

  La restitution des efforts aux commandes de vol est prévue. La présence possible de deux membres d'équipage nécessite une étude particulière qui doit concilier les points suivants

pour les objectifs d'étude choisis : configuration de la cabine et de l'équipage, importance de la vision extérieure jour et nuit pour les deux membres d'équipage et possibilité de restitution pour chacun d'eux. Les conclusions permettent de faire un choix entre une cabine biplace ou deux cabines monoplaces. Dans ce dernier cas, une synchronisation des deux cabines est nécessaire pour la restitution de la vision du monde extérieur et plus généralement pour toutes les informations présentes aux deux postes d'équipage.

- Le système de restitution de la vision du monde extérieur comprend deux sous-ensembles principaux : le sous-ensemble de génération de l'image et le sous-ensemble de visualisation aux postes d'équipage.

Le système global permet principalement de simuler pour un vol tactique, la vision extérieure directe dont dispose l'équipage en vol de jour et une vision du monde extérieur à base de caméra infra-rouge dans le cas du vol de nuit.

Il paraît difficile de couvrir ces deux cas avec les mêmes moyens techniques. De plus, la présence possible de deux membres d'équipage complique sérieusement le problème dans la mesure où en particulier leurs utilisations respectives de la vision extérieure peuvent être totalement indépendantes et parfois contradictoires. Compte-tenu de ces difficultés et du rôle déterminant de ce système dans le SDVEH, il importe d'adopter à son égard une organisation très modulaire permettant de le modifier en fonction des études et de le faire évoluer en fonction des progrès à venir dans ce domaine.

- Les moyens de calcul temps réel sont organisés autour de calculateurs type SEL 32 travaillant sur 32 bits flottants.

Afin d'atteindre les objectifs fixés, le Logiciel doit être conçu de façon très modulaire. En outre, il est écrit en FORTRAN afin d'en rendre la manipulation très facile.

Le module de mécanique du vol doit être programmable en fonction de l'hélicoptère étudié. Il est capable de restituer le comportement du véhicule dans tout le domaine de vol tactique. C'est-à-dire :

- aux basses vitesses
- aux fortes incidences
- aux forts dérapages
- dans l'effet de sol.

Le module du pilote automatique doit être interchangeable en fonction de l'hélicoptère ou du pilote automatique simulé.

Le Logiciel comprend également une série de modules modélisant tout ou une partie des équipements, capteurs et commandes de vol.

De plus, l'intégration d'ARRAY-PROCESSEUR est possible afin d'augmenter la puissance de calcul temps réel du système, en particulier pour la simulation de parties complexes d'un système d'arme.

Le couplage des moyens informatiques à une liaison du type BUS numérique embarqué est possible. Ceci améliore les possibilités d'intégration d'équipements réels au sein du SDVEH.

Les moyens périphériques suivants sont prévus pour faciliter l'exploitation des essais :

- 1 console graphique et alpha numérique
- 1 imprimante
- 1 lecteur de cartes
- Plusieurs disques de 80 Méga octets pour le stockage des programmes et des fichiers
- Des bandes magnétiques de 800 et 1600 BPI pour une vitesse de défilement de 75 IPS
- 1 processeur générateur capable d'élaborer une symbologie superposable à une image vidéo

  - Des écrans TV de contrôle de la vision du monde extérieur aux postes d'équipage
  - Divers instruments identiques à ceux installés aux postes d'équipage.

- Des sous-ensembles sont prévus pour restituer les vibrations et une ambiance sonore en particulier.

- Sur le plan fonctionnel, on remarque le caractère anthopocentrique du simulateur et son souci de replacer l'équipage dans une ambiance aussi proche que possible de celle d'un vol réel en envisageant tous les types de perception auxquels il est soumis, sachant qu'elles jouent un rôle décisif dans le comportement d'un équipage d'hélicoptère.

4.2. FONCTIONNEMENT SIMPLIFIE

On observe enfin la possibilité d'un "fonctionnement simplifié" du SDVEH, sans système de restitution du monde extérieur et sans plateforme de mise en mouvement. Il peut être utilisé de deux façons différentes :

- Tout d'abord, lors de la mise au point du SDVEH
- Puis en exploitation normale du simulateur pour réduire le temps d'immobilisation de l'ensemble des moyens de simulation implantés au Centre d'Essais en Vol d'Istres.

En effet, ce fonctionnement ne met en jeu que des sous-ensembles transportables - le Logiciel et la cabine (appelés pour cette raison Unité Mobile d'Etude) - Tandis que les systèmes de restitution de la vision extérieure et de mise en mouvement sont fixes, installés à demeure à Istres (Unité Lourde d'Etude).

Il sera donc possible de mieux préparer une expérimentation avant de se présenter à Istres. De plus, il sera possible de mener ailleurs qu'à Istres certaines études pour lesquelles la présence des moyens fixes n'est pas indispensable.

Ce fonctionnement doit améliorer la rentabilité du SDVEH.

4.3. PROGRAMME DE DEVELOPPEMENT

Compte-tenu du caractère évolutif d'un simulateur d'étude et de l'intérêt de le doter des plus récents progrès techniques susceptibles d'étendre son champ d'application, il a été choisi de suivre un plan de développement du projet, progressif et respectant des étapes clés.

Ce plan de développement prévoit deux phases, elles-mêmes divisées en processus (voir Planche 4). La première phase a un caractère d'étude tandis que la deuxième est une phase de réalisation du SDVEH qui n'est lancée qu'après analyse des résultats de la première phase et évaluation des coûts.

4.3.1. Phase 1

La première phase est une phase de définition et de conception du SDVEH qui dure douze mois. Elle comprend trois processus :

- Processus 1 FAISABILITE
- Processus 2 DEFINITION
- Processus 3 CONCEPTION

- Le premier processus doit permettre de s'assurer de la faisabilité et de la définition générale du contenu, de certains sous-ensembles du SDVEH en fonction des objectifs et des contraintes cités.

  Elle doit également préciser la façon de valider le simulateur et ses sous-ensembles.

  Les résultats de ce processus sont fondamentaux : ils définissent les possibilités futures d'étude du simulateur et son contenu matériel.

- Le deuxième processus est l'établissement du cahier des charges du SDVEH, fixant précisément les fonctions de chaque sous-ensemble et les échanges entre eux.

- Le troisième processus est l'établissement des spécifications techniques et des liasses de plans pour entreprendre la réalisation effective du SDVEH dès la notification de la phase suivante.

4.3.2. Phase 2

La deuxième phase est une phase de réalisation exploitant les résultats de la Phase 1 s'ils sont définitivement acceptés. Elle dure 24 mois et comprend deux processus :

- Processus 1 DEVELOPPEMENT MISE EN OEUVRE DES DIFFERENTS SOUS-ENSEMBLES
- Processus 2 INTEGRATION

- Le premier processus est consacré à la réalisation concrète des différents sous-ensembles et à leur contrôle sur les lieux de fabrication.

- Le deuxième processus prévoit l'assemblage au Centre d'Essais en Vol d'Istres, des différents sous-ensembles après avoir vérifié leur bon fonctionnement individuel. Il comprend également le contrôle de bon fonctionnement de l'ensemble.

5. POINTS CRITIQUES

Ce projet de SDVEH fait apparaître un certain nombre de points jugés critiques pour l'avenir d'un tel simulateur.

1 La restitution de la vision du monde extérieur est essentielle, notamment pour l'étude du vol tactique. La qualité avec laquelle elle est restituée définit dans une large mesure, l'intérêt du SDVEH. Le cas de la vision de jour paraît le plus délicat à traiter.

2 Le modèle de mécanique du vol doit être capable de restituer en temps réel le comportement du véhicule dans le domaine de vol très varié du vol tactique.

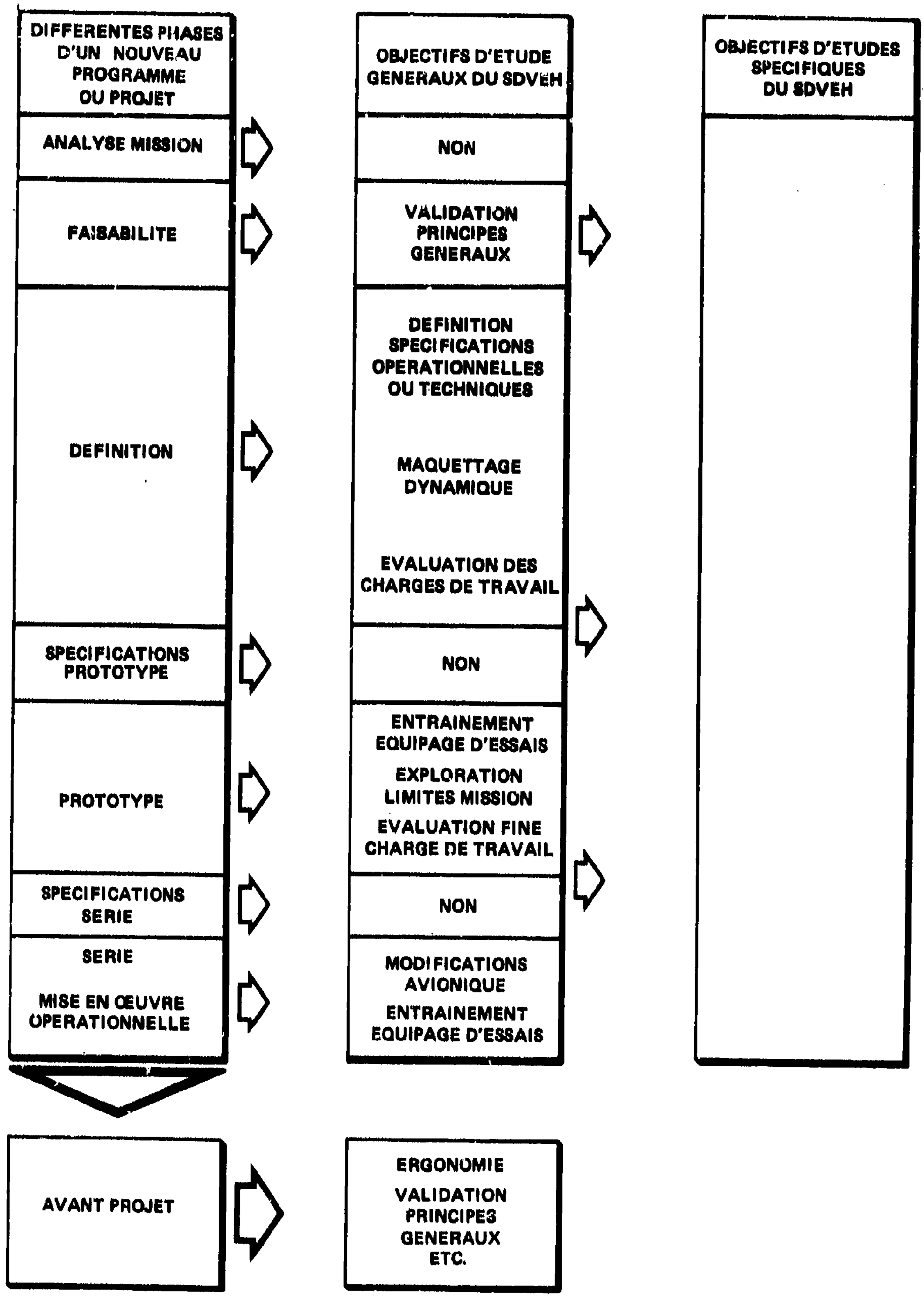
3 La restitution des efforts aux commandes de vol doit être réaliste si l'on ne veut pas désorienter les équipages.

4 Les mouvements de la plateforme supportant la cabine doivent être représentatifs afin de ne pas fournir à l'équipage une fausse information plutôt de nature à la troubler qu'à le renseigner.

5 Enfin, on ne doit pas perdre de vue que sans une bonne aptitude aux reconfigurations et à l'intégration d'un système d'arme, le SDVEH voit son utilité réduite.

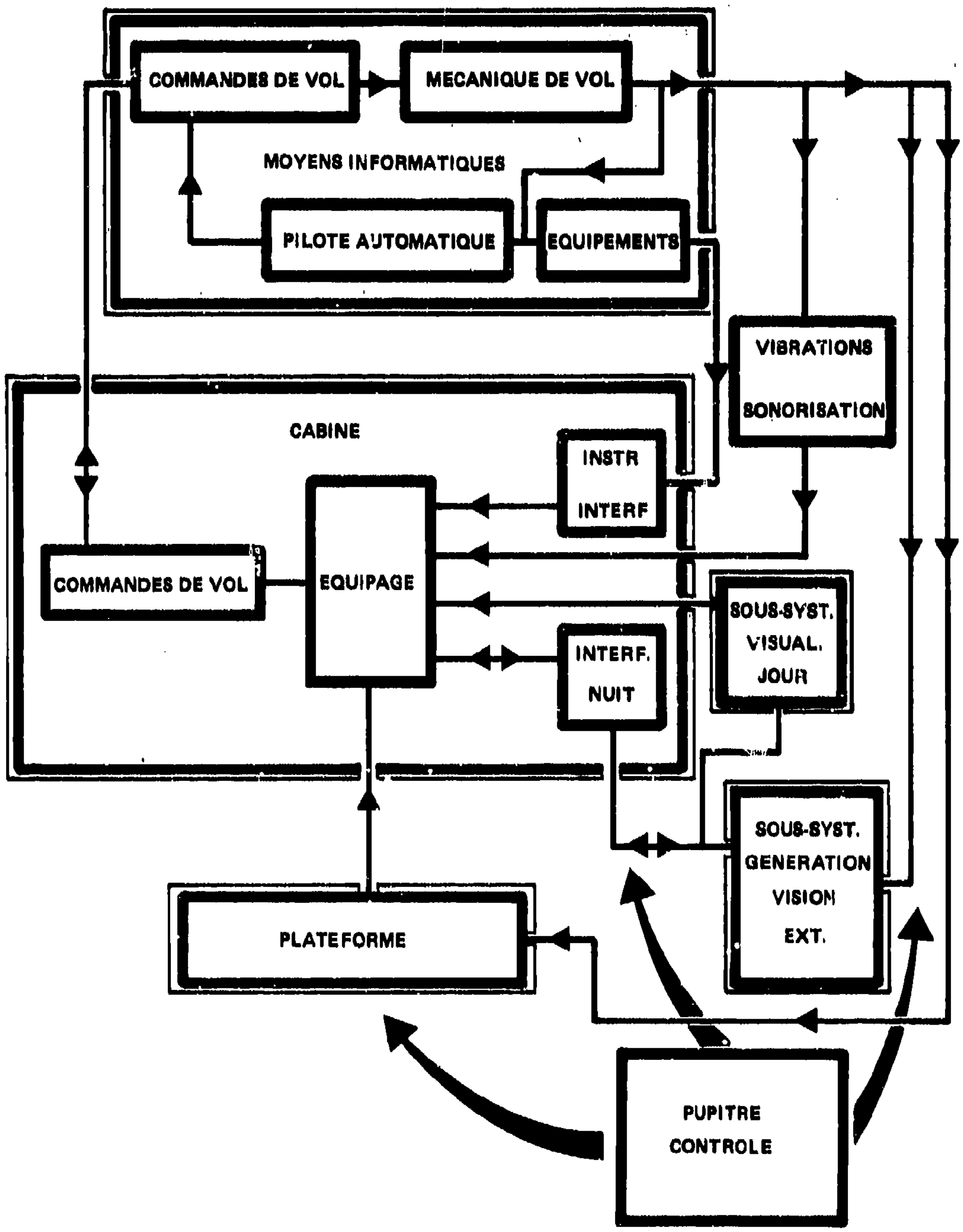
6. CONCLUSION

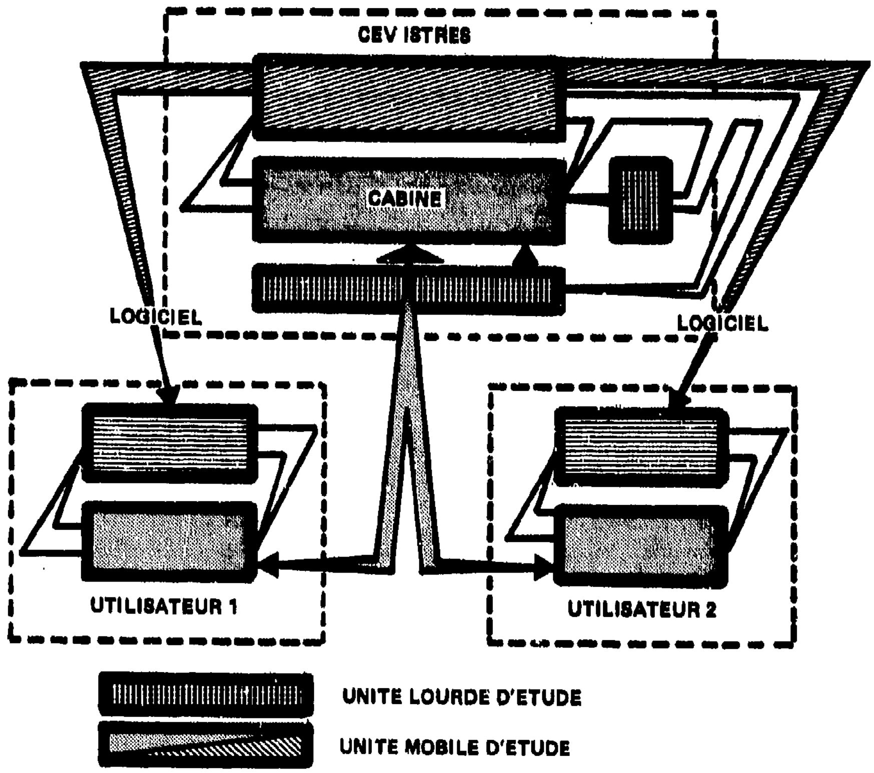
En conclusion, un tel projet résulte de la nécessité de se doter pour les années à venir, de moyens d'étude adaptés pour résoudre à temps les problèmes que posent principalement l'avionique dans le développement d'un nouveau programme ou projet Hélicoptère.



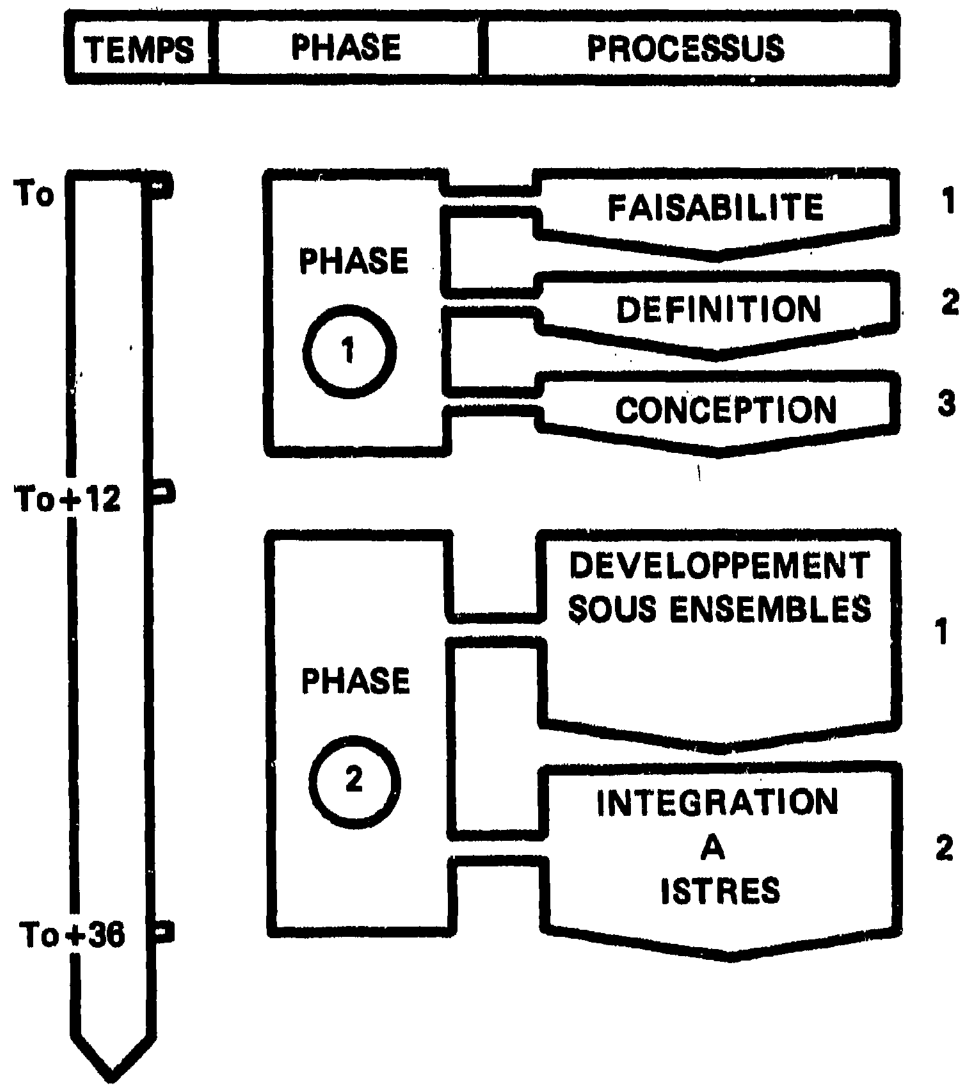
PL.1 OBJECTIFS D'ETUDE

PL.2. ORGANISATION GENERALE DU SDVEH





PL.3 FONCTIONNEMENT SIMPLIFIE



PL.4 PLAN DE DEVELOPPEMENT

COST-EFFECTIVENESS OF FLIGHT SIMULATORS FOR MILITARY TRAINING

Jesse Orlansky and Joseph String
Institute for Defense Analyses
Arlington, Virginia 22202

SUMMARY

The cost and effectiveness of flight simulators used for military training are evaluated in this paper. An analysis of recent cost data shows that modern flight simulators can be operated at costs that range from about 5 to 20 percent that of comparable aircraft. With respect to effectiveness, many studies show that skills learned in flight simulators can be performed successfully in aircraft; this finding applies to a wide variety of tasks, aircraft, types of simulators and level of pilot training. Using the Transfer Effectiveness Ratio as a basis of comparison, it appears that pilots trained in simulators use less flight time to perform various tasks than do those trained only in aircraft; the median amount of flight time saved is about half of the time spent in the simulator. There is a wide variation in the amounts of flight time saved but the reasons for this variation have not been studied. Thus, the critical issue is whether the amount of aircraft time saved is worth the cost of the use of simulators. The cost-effectiveness of flight simulators for training has been examined only in a few recent studies; these show that the procurement cost of simulators can be amortized in about two years. Current research and development on flight simulators center about the need for motion and wide angle visual display systems.

1. INTRODUCTION

"I have always considered the present method of doing all the training on planes as entirely too slow and too expensive. There are certain things which the pilot must do by reflex action without conscious effort. From my experience in teaching years ago I found these things could be done better and more quickly on the ground. . . More training in overcoming. . .acquired reflex actions (e.g., controlling the aircraft rudder in a manner opposite to steering a sled) can be had in one minute on a ground trainer than can be had in an hour in an inherently stable aeroplane such as is used today in training."

Letter from Orville Wright to Charles F. Kettering, March 21, 1941, (McFarland, 1972, p. 1167-1168).

Flight simulators have been available for almost as long as there have been aircraft. For example, the Sanders Teacher could be used for training pilots in England in 1910, about 70 years ago (Figure 1). Modern flight simulators, with wide angle visual systems and moving platforms are, of course, much more complex training devices. This paper evaluates what is known about the cost and effectiveness of flight simulators used for military training.*

A flight simulator can best be viewed as a training device. It permits close observation of pilot performance and immediate feedback and thereby improves learning; it can train pilots in many types of malfunctions not often encountered in flight; it is safe and permits training independent of weather, air traffic and the availability of aircraft; it saves fuel, ammunition, targets, wear and tear on airplanes and, above all, the lives of pilots. But a simulator also has some important disadvantages. Even the most advanced simulators have limited fidelity in their external vision, platform motion and flight equations; they cannot provide the stress and motivation possible only in actual flight; and they are expensive to procure and to operate.

The use of flight simulators has increased markedly in the United States since the oil embargo of 1973; about $300 million will be spent for procurement in Fiscal Year 1979 and about $500 million in Fiscal Year 1980.

2. COST OF OPERATING FLIGHT SIMULATORS AND AIRCRAFT

The first question about the use of flight simulators and aircraft for training concerns how much each cost to operate. For this purpose, we consider only "variable operating costs" which, by definition, include the costs of fuel, oil and lubrication, base maintenance materials, and that portion of depot maintenance which varies with flying hours and replenishment spares. Variable operating costs do *not* include the costs of crew and student salaries or of amortizing the purchase of simulators. We were able to find data on operating costs per hour for 33 aircraft and simulators, as shown in Figure 2. The data are based on actual utilization of aircraft and simulators in FY 1975 and FY 1976.

In absolute terms, the costs of operating simulators range from about $10 to $275 per hour; the costs of operating aircraft range from about $60 to $3600 per hour. For the same aircraft, the ratios of simulator/aircraft operating cost vary from about 5 to

*This study was performed for the Deputy Director of Defense Research and Engineering (Research and Advanced Technology), United States of America.

20 percent. The median value is about 12 percent. Thus, it is clear that it costs less to operate a flight simulator than the comparable aircraft. This finding is not a surprise. The cost advantage of flight simulators says nothing about their effectiveness for training.

3. THE EFFECTIVENESS OF FLIGHT SIMULATORS

One way to evaluate the effectiveness of a flight simulator is to ask experienced pilots to judge whether that simulator flies about the same way the actual airplane does. This is the test of "fidelity of simulation". Since we were concerned with the use of flight simulators for flight training, we were particularly interested in whether skills learned in a simulator carry over to an airplane. That is called "transfer of training", which is defined below. For our purposes, we wanted to know how well pilots trained in simulators perform the same tasks in the air compared to those trained only in aircraft. We also wanted to know whether training in simulators saves any flight time. There are 33 studies performed from 1939 to 1977 which provide information relevant to these issues.

The simulators used in these studies varied widely with respect to types of aircraft, visual and motion systems; about half the studies were performed after 1970 when more modern simulators began to be available. The pilots used in these studies vary with respect to level of experience; a wide range of flying tasks were employed. These studies show that pilots trained in simulators perform in aircraft as well as those trained only in aircraft, at least as measured by Instructor Pilot's ratings. This finding applies generally to such tasks as cockpit checkout, flight procedures, instrument flying, take-off and landing; a few recent studies extend these findings to more acrobatic maneuvers and to air-to-ground gunnery. Simulator training also seems to save flight time.

However, the results of these studies are not reported in a common format which permits one to generalize on how much flight time can be saved by simulators. The Transfer Effectiveness Ratio (TER), as defined in Figure 3, can be used to show the amount of flight time saved as a function of the amount of time spent on training the same task in a simulator. Its use for comparative evaluation was proposed by Stanley Roscoe (1971) in 1971.

Most studies of flight training in simulators, including the more recent ones, do not report Transfer Effectiveness Ratios. However, enough information was available in 22 studies from 1967 to 1977 to compute the 34 TERs shown in Figure 4. These TERs apply, variously, to instrument training, transition training, flight procedures, simulators with or without motion and so on. Overall, the TERs vary from -0.4 to 1.9, with a median value of 0.48. This may be interpreted as follows:

Pilots trained in simulators use less flight time than those trained only in aircraft. The median amount of flight time saved is about half (0.48) of the time spent in the simulator. There is one negative value (-0.4) which means that pilots trained in a simulator in that study used more aircraft time than those trained only in aircraft. This finding has not been confirmed and there is insufficient information with which to explain this case of "negative transfer"; it may be due to use of an inadequate simulator. In any case, it is helpful to understand that not all uses of flight simulators necessarily save training time.

There are seven cases where the TER is one or more. These cases mean that more than one hour of flight time was saved for every hour spent in the simulator. This result should not be too surprising. It is possible to practice a task more often in an hour in a simulator than in an aircraft; e.g., one doesn't have to go around the traffic pattern to shoot a landing; one doesn't have to take time to set up a flight condition as in an airplane, because it can be set up instantly by the computer; one can get more feedback about performance in a simulator than in an airplane, and so on.

However, the high positive TERs and the one negative TER are extreme values; the middle 50 percent of all values fall between 0.25 and 0.75; the median TER of the entire distribution is 0.48.

The TERs shown previously were divided into three groups based on the experience level of the pilots which, in effect, also describe the use of simulators for different types of training:

Level of Experience	Type of Training
highly experienced	transition flight procedures
graduate	transition instrument
undergraduate	familiarization instrument

As shown in Figure 5, undergraduate pilots trained in simulators for familiarization and instrument flying save more aircraft time than more advanced pilots trained in simulators for transition flying and flight procedures. However, it costs more per hour to fly an advanced aircraft than one used by undergraduate pilots, but that is not considered here.

In a recent study, Transfer Effectiveness Ratios were determined for 24 different maneuvers when the CH-47 helicopter flight simulator was used for transition training (Holman, 1979). The findings (Figure 6) show that the effectiveness of this simulator for training varies widely among the maneuvers for which it was used in this study. The TERs range from 0.0 to 2.8. Clearly this simulator should *not* be used for training on certain maneuvers. It appears that this simulator has limitations for training, probably for tasks that depend significantly on visual simulation.

Based on these studies, the effectiveness of flight simulators may be summarized as follows:

1. Simulators are effective for training pilots under many different conditions. Simulators have been shown to be effective for training undergraduate and graduate pilots, for training on many different types of aircraft, and for training on different types of tasks (e.g., landing, instrument flight, flight procedures, flight familiarization). This finding also applies generally to the effectiveness of simulators with a variety of performance capabilities, e.g., with or without vision, with or without motion.

2. Effectiveness varies widely. There is a wide range in the degree of effectiveness reported with the use of flight simulators. Little systematic attention has been given to examining the factors that may influence the effectiveness of simulators. Since most studies do not use common measures, it is difficult to understand the reasons for the wide range in the effectiveness of different types of simulators or in their use for training on different tasks.

3. Flight simulators save aircraft time. Virtually all studies (21 out of 22) show that the use of flight simulators saves aircraft time. Pilots trained on specific tasks in simulators need less time to perform these tasks in aircraft than do pilots trained on the same tasks only in aircraft.

4. Effectiveness does not imply cost-effectiveness. The fact that flight simulators are effective for training does not necessarily imply that they are worth what they cost to operate.

We turn next to the question of the cost-effectiveness of flight simulators.

4. COST-EFFECTIVENESS OF FLIGHT SIMULATORS

In order to estimate the cost-effectiveness of flight simulators for training, we need data on the cost *and* the effectiveness of simulators and of aircraft for training pilots on particular maneuvers or tasks. Such data have been reported in only a few studies.

A study by Povenmire and Roscoe (1973) shows exactly how the cost-effectiveness of a flight simulator should be evaluated. Student pilots were given either 0, 3, 7, or 11 hours of training on the Link GAT-1 simulator before being trained in an airplane. Figure 7 shows the number of hours needed by each group to pass the final flight check, and the number of aircraft hours saved by the simulator when compared to hours needed by those trained only in the airplane. To the best of our knowledge, this is the only study performed so far in which the amount of time spent in a simulator was varied systematically; all other studies tend to use a fixed amount of simulator time.

Figure 8 shows the Cumulative Transfer Effectiveness Ratio and the Incremental Transfer Effectiveness Ratio as functions of the amount of time spent in the simulator (CTER is the same as TER). Both ratios are reduced as the amount of time spent in the simulator increases. This is an important finding because it permits us to determine when the marginal transfer effectiveness of the simulator has been reached. A useful criterion is the ratio of the costs of operating a particular simulator and aircraft. In this case, the simulator/aircraft operating cost ratio is $16/22 per hour or 0.73. Therefore, training in the simulator is cost-effective until the Incremental Transfer Effectiveness Ratio drops below the simulator/aircraft operating cost ratio. This occurs at about 4 hours in the GAT-1 when it is used for training student pilots to pass the final flight check for a private pilot's license.

The Piper Cherokee is a simple airplane and it is inexpensive to operate, i.e., $22 per hour. Many military aircraft cost far more to operate and, as reported earlier, most simulator/aircraft operating cost ratios range between 0.05 and 0.20. If those ratios applied to the present data, it would have been economical to use the simulator for longer periods, perhaps as long as 10 to 20 hours.

The Coast Guard operates two helicopters, the HH-52A and the HH-3F (Isley, Corley and Caro, 1974). In 1974, it introduced the Variable Cockpit Training System. This simulator has two cockpits and can simulate either or both helicopters; each has a motion base with six degrees of freedom but no visual system. The procurement cost was $3.1M (Figure 9); operating costs of the simulator are very much less than for the helicopters.

Figure 10 shows the number of aircraft and simulator hours per pilot required to complete various types of training before and after introduction of the simulator. Aircraft hours required per pilot were reduced in all cases. The total cost of flight training used to be $3 million per year; now the total cost of flight time and simulator time is $1.6 million per year, a realized benefit of almost $1.5 million per year.

There is also an additional (estimated) benefit because the simulator is now used instead of the helicopter in preparation for the check ride and emergency procedures tests in proficiency training. This is estimated to cost $106 thousand per year for the simulator but it avoids costs of about $1.1 million per year for the helicopters.

Thus, the procurement cost of the VCTS can be amortized in either 2.1 years (Figure 11) or in 1.2 years, depending on which benefits are used to make this assessment.

In 1977, Browning, Ryan, Scott, and Smode (1977) compared the cost and effectiveness of two programs for transition training of Naval pilots to fly the P-3C, a four-engine turboprop aircraft used in anti-submarine warfare. The two programs involve the use either of an old simulator (2F69D) or a new one (2F87F); both simulators provide individual and crew training for the pilot, co-pilot and flight engineer. The same cockpit procedures trainer (2C45) is used in both programs. These devices are described below:

- Cockpit Procedures Trainer, Device 2C45. Provides training in power plant management and systems procedures for normal and emergency operations. This device is actually an obsolete P-3 operational flight trainer from which flight dynamics, motion, and unneeded systems have been removed.

- Operational Flight Trainer, Device 2F69D. This trainer is a solid state analog device (1966 era) which simulates flight dynamics, flight systems, navigation, and communications for P-3A/B aircraft. It provides motion (3 degrees of freedom) but no visual simulation.

- Operational Flight Trainer, Device 2F87F. This trainer is a digital device which simulates the P-3C Orion aircraft. It provides motion (6 degrees of freedom) and vision (50° wide x 38° high) by means of a TV model board system (15 nmi x 5 nmi) for low-altitude maneuvers such as takeoff, landing, and instrument approaches. It replaces the 2F69D.

All pilots were newly designated first-tour Naval Aviators who possessed Standard Instrument Cards. All had completed undergraduate multi-engine training on the S-2, a small, two-engine propeller-driven aircraft. Hours given to training in simulators prior to flight are shown in Figure 12: 22 hours in the old program, 40 in the new one. After training in the simulator, performance was measured in the aircraft on 20 of the 45 tasks specified in the Familiarization and Instrument phase of transition training, (e.g., engine start, brake fire, abort take-off, approach, three engine landing). The critical data were the hours required by each group to perform these tasks proficiently in the aircraft, i.e., as judged acceptable by the Instructor Pilot. The control group required 15 hours in the aircraft per pilot, the experimental group required 9. There was no difference between the groups in flight proficiency in the air. These findings are supported by more recent work at VP-30 (Browning, Ryan and Scott, 1978).

The new P-3C simulator costs $4.2 million (Figure 13). Compared to the control program, the experimental program is estimated to save $2.5 million per year (assuming a projected load of 200 pilots per year). On this basis, the procurement cost of the new simulator would be amortized within two years.

An analysis of investment costs also favors the new program (Figure 14). Based on required flight hours, the control program would require 7 aircraft, the new one 4.2 aircraft (at $13.7 million per aircraft). The investment cost of the new program is $63.2 million compared to $98.7 million for the old one. The 10-year life cycle cost of the new program is $81 million compared to $125 million for the old one.

One airline provided an analysis of its costs for the use of simulators and aircraft for training in 1976 (Figure 15). Simulators are used for training purposes for 26,000 hours each year and, in addition, aircraft for over 1,100 hours. The cost of these training hours was $6.8 million in 1976. This airline estimated what it would cost, also in 1976, if all these training hours had to be performed only in aircraft. That total would be about $32.1 million a year. This airline estimates that its annual training costs for simulators and aircraft are about 21 percent of what they would be if they had to depend only on aircraft.

The flight simulators used by this airline cost $17.5 million (Figure 16) and the airline estimates that their use saves $25 million per year. At this rate, the procurement of flight simulators can be amortized in less than nine months.

These four studies of cost-effectiveness support the use of flight simulators (Figure 17). Use of the Navy P-3C simulator and the Coast Guard VCTS simulator saved sufficient flight time to amortize procurement costs within two years. An analysis provided by an airline suggests an even shorter amortization period.

5. DISCUSSION

Most simulator/aircraft operating cost ratios fall in the range of 0.05 to 0.20. The use of flight simulators appears to save flight time in aircraft. The range of these values, expressed as Transfer Effectiveness Ratios, varies from close to zero to well over one, with a median at about 0.50. Thus, there is a clear implication that flight simulators can be cost-effective for training providing careful attention is given to their use for tasks and maneuvers where the transfer effectiveness ratios are greater than the simulator/aircraft operating cost ratios. There is also a clear indication that the incremental transfer effectiveness ratio decreases as training time increases; thus,

it is possible to determine an optimum point at which training for particular tasks should shift from the simulator to the aircraft. Only a few studies of cost-effectiveness have actually been conducted. Here, it appears that the cost of procuring flight simulators can be amortized within about two years.

Some recent developments in flight simulators can significantly affect their cost and effectiveness. A six degree of freedom synergistic motion platform can cost up to $0.6 million. A series of studies since 1974 have shown that there is no difference in performance in aircraft between pilots trained in simulators with motion and pilots trained without motion (Koonce, 1974; Jacobs and Roscoe, 1975; Woodruff and Smith, 1974; Gray and Fuller, 1977, Woodruff, Smith et al., 1976; Martin and Waag, 1978). Although more work remains to be done, it appears that modern flight simulators for center thrust aircraft, with good visual systems, do not need platform motion. Recent procurements of F-16 and A-10 simulators by the Air Force do not include platform motion. It is still an open question whether platform motion is needed in simulators for wide bodied aircraft.

Incidentally, a concern with improving the fidelity of flight simulators led to the improvement of platform motion over the past 15 years. It is, of course, true that pilots perform better in simulators with motion than in simulators without motion. Until Koonce's study in 1974, no one seriously questioned whether platform motion in simulators contributes anything to performance in aircraft. The answer so far seems to be "not much". These recent findings also suggest that, except possibly to improve pilot acceptance, the test of fidelity of simulation may not always give us a good answer.

New computer-generated visual systems can provide types of training in simulators that have not been possible up to now. They can present scenes needed, for example, for training in aerial refuelling, air-to-air combat, and nap-of-the-earth flying. Visual systems for flight simulators are very impressive devices. So is their cost, which is now in the range of $6 to $8 million per copy. The real question concerns the degree of realism required to make visual displays useful for such types of training. Very little data are now available to help us specify the visual requirements for this most expensive component of a modern flight simulator. There is one study in which Air Force pilots were trained in simulators to land a B-707 using one of three different visual simulation systems and then measured for their ability to land a KC-135 aircraft, the tanker version of the B-707 (Thorpe,Varney et al.,1978). The visual scenes were produced by a day computer-generated imagery (CGI) system, a day TV model board system and a night-only computer-generated imagery system. Pilot performance on landing the aircraft was superior for those trained on the two CGIs than for those trained on the TV model board; there was no difference between the two CGI systems as far as landing performance is concerned. If we accept the results of this one study, the less expensive, night-only CGI is all we need for training pilots how to land. In all fairness, further studies on other maneuvers and other types of simulators are needed before we can specify what type of visual imagery is good enough for various types of training. Here again, imagery with the greatest fidelity and highest cost may not be all that necessary.

One final point. It is quite likely that flight simulators will be found to be cost-effective and as a result, there may be more pressure to reduce flying hours. Flight simulators, however useful, are not a substitute for training in aircraft. Military training must proceed from simulators to aircraft and there is some minimum amount of flight time required below which one cannot go. This is necessary to maintain combat skills and to exercise support systems, such as maintenance and command and control, on which military readiness depends. More attention must clearly be given to establish what these minimum flying hours should be.

6. CONCLUSIONS

a. Flight simulators cost less to operate than do aircraft; most simulator/aircraft operating cost ratios fall within the range of 0.05 to 0.20.

b. Flight simulators save flight time. Transfer Effectiveness Ratios vary widely, with a median value of about 0.50. This means that about half the time spent in simulators shows up as savings in flight time.

c. The cost of procuring flight simulators can be amortized in about two years.

d. Research and development is needed to improve our knowledge about the optimum use of simulators for various types of flying tasks. There is a need to establish the optimum point, in terms of effectiveness and of cost, at which training should shift from the simulator to the aircraft. There is also a need to examine the need for platform motion in simulators for wide bodied aircraft and for the degree of realism needed in new visual displays.

e. There is a need to establish the minimum amounts of flying hours needed to maintain combat skills and to exercise support systems.

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Figure 1: THE SANDERS TEACHER, ENGLAND, 1910

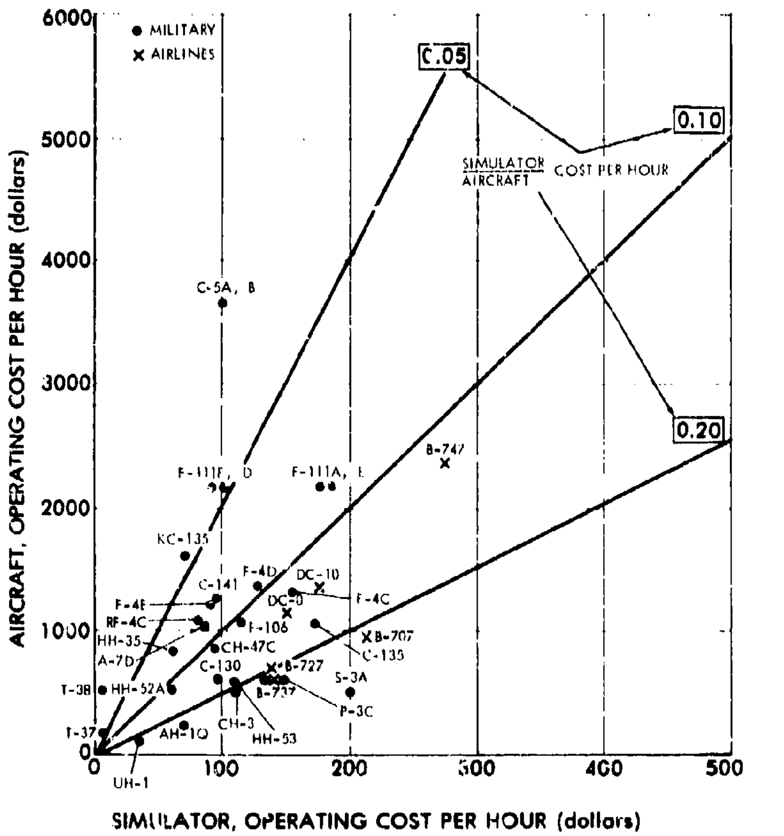


Figure 2: VARIABLE OPERATING COSTS PER HOUR FOR 33 SIMULATORS AND AIRCRAFT, FY 1975 AND FY 1976

$$TER = \frac{Y_o - Y_x}{X}$$

Y_o = AIRCRAFT TIME, CONTROL

Y_x = AIRCRAFT TIME, EXPERIMENTAL

X = SIMULATOR TIME, EXPERIMENTAL

Figure 3: TRANSFER EFFECTIVENESS RATIO (TER)

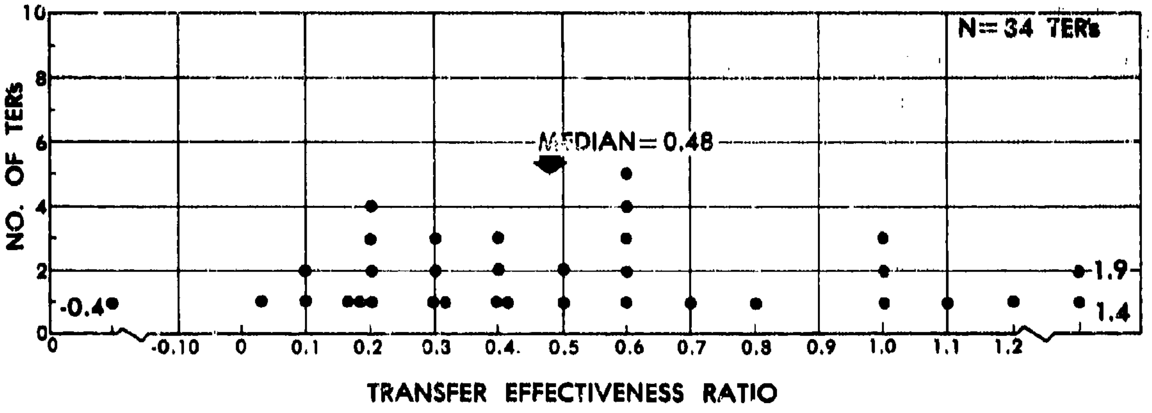


Figure 4: TRANSFER EFFECTIVENESS RATIOS FROM 22 STUDIES (1967-1977)

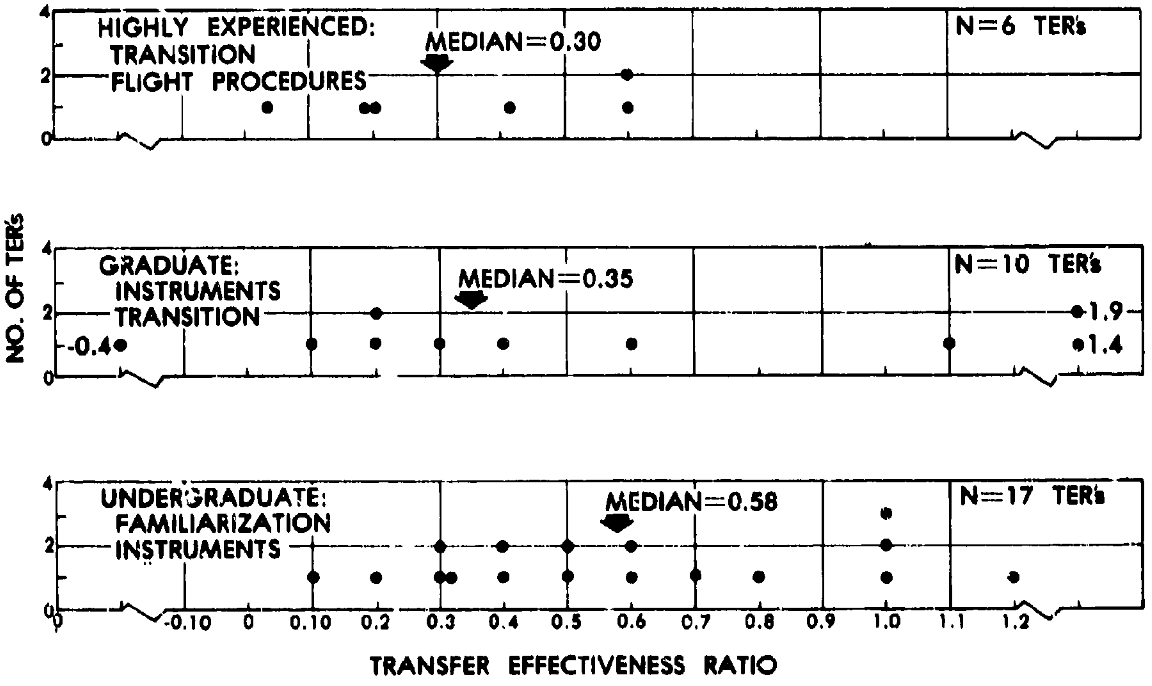


Figure 5: TRANSFER EFFECTIVENESS RATIOS AND PILOT EXPERIENCE

MANEUVER	TER
Four wheel taxi	2.80
Cockpit run up	1.50
SAS off flight	1.33
Deceleration	1.25
Maximum take off	1.25
General air work	1.00
Steep approach	1.00
Two wheel taxi	1.00
Confined area recon	1.00
Hovering flight	.79
Normal take off	.75
Confined area approach	.75
Landing from hover	.69
External load briefing	.67
Take off to hover	.63
Traffic pattern	.61
Shallow approach	.58
Normal approach	.53
Confined area take off	.50
External load take off	.50
External load approach	.50
Pinnacle recon	.50
Pinnacle take off	.33
Pinnacle approach	.00

Source: Holman, 1979.

Figure 6: TRANSFER EFFECTIVENESS RATIOS FOR 24 MANEUVERS, CH-47 FLIGHT SIMULATOR (TRIALS TO CRITERION) (Source: Holman, 1979)

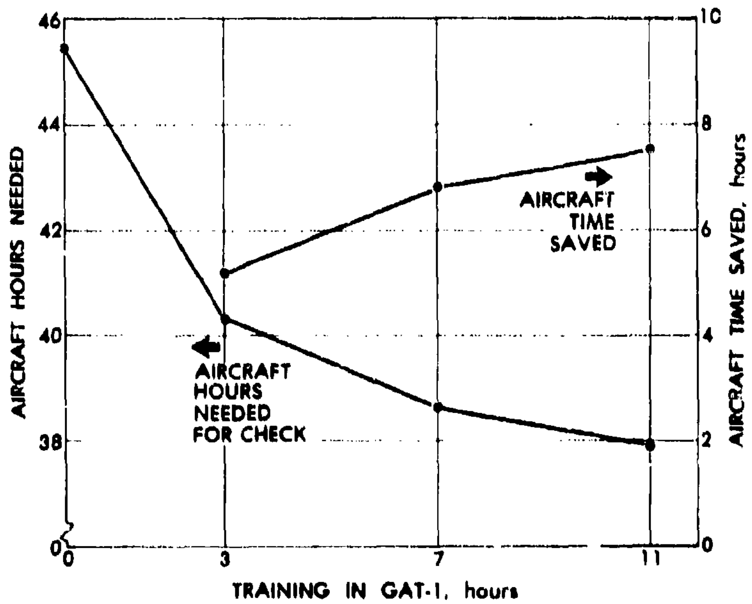
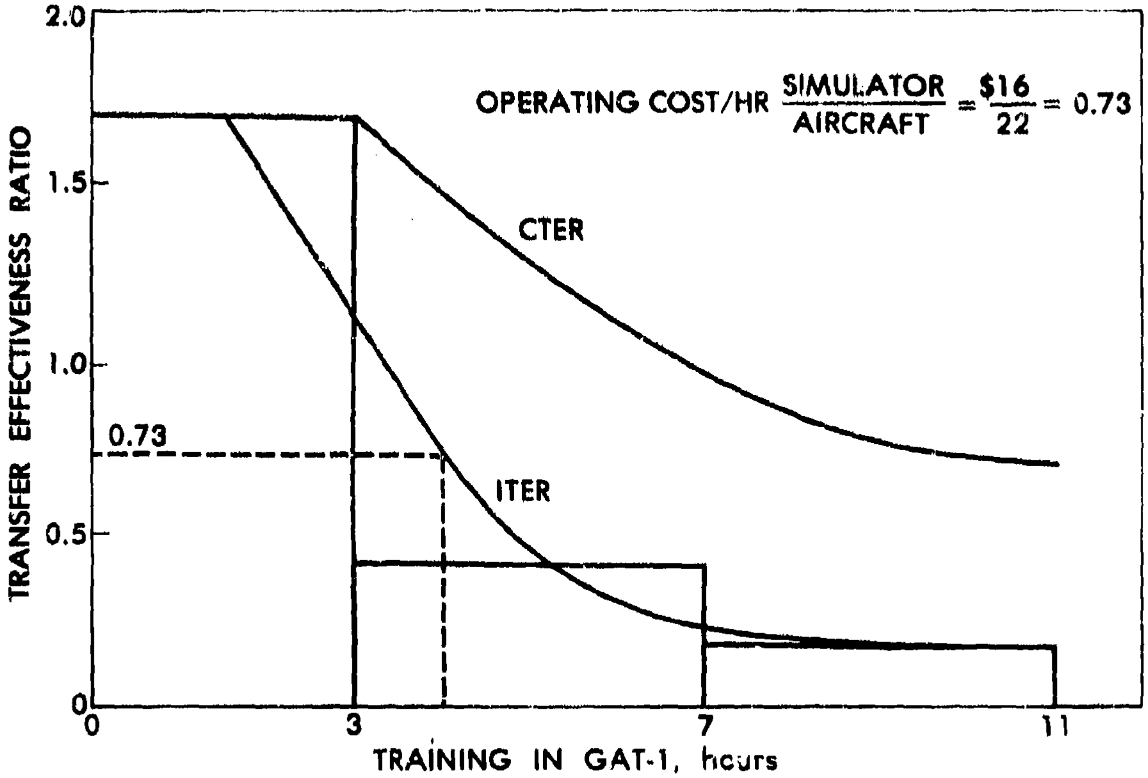


Figure 7: HOURS NEEDED FOR FINAL FLIGHT CHECK, PIPER CHEROKEE (Source: Povenmire and Roscoe, 1973)



Source: Povenmire and Roscoe (1973)

Figure 8: INCREMENTAL TRANSFER EFFECTIVENESS RATIO (ITER) AND OPERATING COST RATIO (Source: Povenmire and Roscoe, 1973)

PROCUREMENT COST, VARIABLE COCKPIT TRAINING SYSTEM (VCTS)	$3.1M
OPERATING COST PER HOUR (1974 DOLLARS)	
HH-52A	$504
HH-3F	815
VCTS	59

Figure 9: HELICOPTER TRAINING, U.S. COAST GUARD, 1974

TYPE OF TRAINING	PILOTS/YR	BEFORE FLIGHT HRS	BEFORE COSTS (000)	AFTER FLIGHT HRS	AFTER SIMULATOR HRS	AFTER COSTS (000)	BENEFITS (000)
REALIZED BENEFITS							
HH-52A TRANSITION	30	31	$ 469	28	9	$ 439	$ 30
QUALIFICATION	18	78	708	36	11	338	370
PROFICIENCY	300	3	454	0	6	106	348
HH-3F TRANSITION	32	36	939	23	15	628	311
PROFICIENCY	200	3	489	0	8	94	395
TOTALS	580		$3059			$1605	$1454
ESTIMATED BENEFITS							
HH-52A PROFICIENCY	300	3	454	0	3	53	401
HH-3F PROFICIENCY	200	4.5	734	0	4.5	53	681
TOTALS	500		$1188			$ 106	$1082

Figure 10: ESTIMATED TRAINING COSTS IN THE COAST GUARD BEFORE AND AFTER INTRODUCTION OF THE VCTS SIMULATOR, 1974

PROCUREMENT COST OF VCTS	$3.1M
REALIZED BENEFIT PER YEAR	$1.5M
ESTIMATED BENEFIT PER YEAR	1.1
TOTAL	$2.6M

$$\frac{\text{PROCUREMENT COST}}{\text{REALIZED BENEFIT}} = \frac{\$3.1\text{M}}{1.5 \text{ PER YEAR}} = 2.1 \text{ YEARS}$$

$$\frac{\text{PROCUREMENT COST}}{\text{TOTAL BENEFIT}} = \frac{\$3.1\text{M}}{2.6 \text{ PER YEAR}} = 1.2 \text{ YEARS}$$

Figure 11: AMORTIZATION OF VCTS, U.S. COAST GUARD

DEVICE	HOURS REQUIRED PER STUDENT CONTROL N=16	HOURS REQUIRED PER STUDENT EXPERIMENTAL N=27	OPERATING COST PER HOUR
COCKPIT PROCEDURES TRAINER (2C45)	13	16	$104
OPERATIONAL FLIGHT TRAINER (2F69D)	9	--	134
OPERATIONAL FLIGHT TRAINER (2F87F)	--	24	144
AIRCRAFT P-3C	15	9	2284
TOTAL HRS	37	49	
TOTAL COST PER YEAR (200 PILOTS)	$7.1M	$4.6M	

Figure 12: PILOT TRAINING ON P-3C, ANTI-SUBMARINE WARFARE

PROCUREMENT COST DEVICE 2F87F	$4.2M
OPERATING COSTS PER YEAR (200 PILOTS)	
CONTROL	$7.1M
EXPERIMENTAL	4.6
SAVINGS	$2.5M PER YEAR

$$\frac{\text{PROCUREMENT COST}}{\text{SAVINGS PER YEAR}} = \frac{\$4.2\text{M}}{2.5\text{M/YR}} = 1.7 \text{ YEAR}$$

Figure 13: AMORTIZATION OF P-3C SIMULATOR

DEVICE	PRESENT VALUE	CONTROL		EXPERIMENTAL	
		N	COST	N	COST
CPT (2C45)	$1390K	1	$1390K	1	$1390K
OFT (2F69D)	1396	1	1396		
OFT (2F87F)	4225			1	4225
AIRCRAFT P-3C	13.7M	7	95,900	4.2	57,540
TOTAL			$ 98.7M		$ 63.2M
10-YEAR LIFE CYCLE COST (DoD1 7041.3)			$125M		$ 81M

Figure 14: P-3C INVESTMENT COSTS

AIRCRAFT	TOTAL TRAINING HOURS		COSTS		SIMULATOR & AIRCRAFT AS PERCENTAGE OF AIRCRAFT-ONLY COSTS
	SIMULATOR	AIRCRAFT	SIMULATOR & AIRCRAFT (ACTUAL)	AIRCRAFT ONLY (ESTIMATE)	
A	3,511	186	$1.2M	$ 6.0M	19%
B	8,997	272	2.1	10.6	20
C	12,277	547	2.9	11.8	25
D	1,262	118	0.6	3.7	17
TOTAL	26,047	1,123	$6.8M	$32.1M	21%

Figure 15: ANALYSIS OF TRAINING COSTS BY ONE AIRLINE, 1976

PROCUREMENT COST	
SIMULATORS	\$17.5M
COST OF TRAINING	
AIRCRAFT ONLY	\$32.1M PER YEAR (ESTIMATE)
SIMULATORS AND AIRCRAFT	6.8 PER YEAR (ACTUAL)
SAVINGS	\$25.3M PER YEAR (ESTIMATE)

$$\frac{\text{PROCUREMENT COST}}{\text{SAVINGS PER YEAR}} = \frac{\$17.5\text{M}}{\$25.3\text{M PER YEAR}} = 8.3 \text{ MONTHS}$$

Figure 16: ESTIMATES OF AMORTIZATION OF SIMULATORS USED BY AN AIRLINE

	APPLICATION	PILOT LOAD	ESTIMATED AMORTIZATION OF SIMULATOR
PRIVATE PIPER CHEROKEE GAT-1	FINAL FLIGHT CHECK	—	ESTABLISHES OPTIMUM USE OF SIMULATOR
NAVY P-3C 2F87F	TRANSITION TRAINING	200	2 YEARS
COAST GUARD HH-52A HH-3F VCTS	TRANSITION, PROFICIENCY TRAINING	500	2 YEARS
AIRLINE	TRANSITION, RECURRENT TRAINING	—	9 MONTHS

Figure 17: SUMMARY OF COST-EFFECTIVENESS STUDIES

UTILISATION D'UN LANGAGE EVOLUE POUR LES SIMULATEURS D'AVIONS

Michel G. DREYFUS

THOMSON-C.S.F - SIMULATEURS LMT

3 AVENUE ALBERT EINSTEIN

78192 TRAPPES CEDEX FRANCE

SUMMARY

Until recently, flight training simulator computers have generally been programmed in assembler languages which have proven their efficiency. The computers currently available for flight simulators are capable of being programmed in higher level languages such as FORTRAN which are expected to provide analysts with a more accessible data processing tool.

During current contracts for commercial aircraft flight simulators, LMT is writing simulation programs for the same aircraft in both assembler and in FORTRAN. This experience has provided a valuable insight into the advantages and disadvantages of both methods.

This paper reviews the impact of each method on the analytical and programming methods employed at each stage of program writing, debugging and modification. The consequences of computing power and memory capacity are also discussed.

INTRODUCTION

Le choix d'un langage de programmation dans les systèmes scientifiques temps réel a toujours été un sujet très controversé. De nombreux langages évolués ont été développés, et utilisés, mais aucun n'a fait l'unanimité.

Les simulateurs d'entraînement au pilotage, pour des raisons économiques, doivent utiliser des calculateurs de la gamme dite "Mini ou industrielle".
L'unité de traitement d'un simulateur doit exécuter cycliquement un grand nombre d'équations mathématiques et logiques dans un temps imposé par la fréquence des phénomènes à simuler, et inférieur au retard perceptible par un pilote.
C'est pourquoi la puissance de calcul du système est toujours un élément prédominant à considérer lors de la conception.

Le langage de programmation, par contre, peut être différent suivant les applications ou les Clients.

L'Armée Américaine dans un but de standardisation a imposé l'utilisation du FORTRAN pour les simulateurs d'entraînement. Les simulateurs de vol réalisés pour l'entraînement des équipages de Compagnies Aériennes utilisent depuis plus de quinze ans des calculateurs numériques universels programmés en langage assembleur.

Ces calculateurs ont toujours cependant possédé un compilateur FORTRAN, langage largement répandu dans le domaine scientifique, en particulier dans la simulation d'étude.

Aujourd'hui ce langage fait une offensive sérieuse sur le marché des simulateurs d'avions commerciaux, bien qu'il n'ait pas encore réussi à convaincre tous les utilisateurs.

Les Compagnies Aériennes réunies à Montréal le 1er Juin 1978 (IATA Flight Simulator Technical Sub-committee) ont posé pour la première fois la question.

Le comité se mit d'accord pour considérer que l'utilisation d'un langage évolue pourrait devenir un standard dans le futur, mais qu'à ce stade d'expérience il n'était pas prêt à recommander l'utilisation du FORTRAN.

Jusqu'à ces dernières années, les programmes écrits en FORTRAN sur les mini-calculateurs étaient peu performants compte tenu des calculs en virgules flottantes, du format des mots de 16 bits, des difficultés d'adressage et d'un répertoire d'instruction limité.

Seul le savoir faire du programmeur et les calculs en virgule fixe permettaient des temps d'exécution des programmes compatibles avec la fréquence de répétition des calculs.

Mais la complexité croissante des systèmes à simuler et les améliorations demandées par les utilisateurs ont accru la puissance demandée plus vite que la rapidité des mémoires.

L'arrivée sur le marché de nouveaux calculateurs, classés dans la gamme "Mini" par leur prix, mais ayant des performances comparables à celles des calculateurs réservés précédemment à des centres de calcul importants, (format de mots de 32 bits et opérations en virgule flottante ayant des temps d'exécution du même ordre de grandeur que celle en virgule fixe), a fait ressurgir le FORTRAN, aidé par une large publicité faite par les constructeurs annonçant des coefficients de foisonnement (expansion due au langage) suffisamment faibles pour être convaincants.

Dans les discussions entre les fervents de langages évolués d'une part et du langage Assembleur d'autre part, s'opposent généralement des partisans farouches de l'une ou l'autre technique, séparés par une incompréhension mutuelle. En effet, les partisans du langage évolué ont souvent, utilisé uniquement des langages évolués, et les partisans du langage assembleur ont une pratique constante de ce type de langage.

Une comparaison objective des avantages et inconvénients réciproques d'un langage assembleur et d'un langage évolué pour un système donné est donc difficile, car rares sont les réalisations comparables effectuées avec ces deux langages, sur un calculateur identique, à une même époque et par des équipes de niveau ou de formation similaire.

Notre Division a réalisé récemment deux simulateurs de l'avion Airbus A300, programmés l'un en langage Assembleur et l'autre en FORTRAN.

Le calculateur utilisé est le SEL 32/55.

Les conditions ont donc été remplies pour réaliser une évaluation comparative des deux méthodes.

Ce papier rend compte d'un premier bilan de cette expérience.

Cette étude a été entreprise avec l'aide du Ministère de l'Industrie.

2. CONFIGURATION DU SYSTEME ETUDIE

Les avantages et inconvénients d'un langage de programmation étant spécifiques à l'application, nous décrivons les caractéristiques principales du système pour lequel nos conclusions sont applicables. Le système concerné est un simulateur d'entraînement au pilotage de l'avion AIRBUS A300.

2.1 Entrées-sorties

Du point de vue entrées-sorties industrielles, le système doit pouvoir traiter par seconde environ 100.000 entrées-sorties binaires et 5000 entrée-sorties analogiques.

Le système gère également en temps réel une base de données sur disque et deux tubes cathodiques utilisés par les instructeurs pour intervenir sur le système.

De plus 1600 mots sont échangés par seconde avec un processeur traitant des problèmes de simulation de commandes de vol.

Ces chiffres montrent que, contrairement aux simulateurs d'études, les programmes de traitement logique prennent une place importante dans le système.

2.2 Capacité mémoire

Les programmes de simulation de systèmes avions écrits en Assembleur représentent 62 Kmots de 32 bits. Ce total est de 90 Kmots pour l'ensemble équivalent en FORTRAN.

A chaque système avion correspond un programme dont l'importance peut varier de 0,5 Kmots à 8 Kmots (en assembleur). Ces programmes communiquent par un bloc de valeurs communes (DATA POOL) de 4 Kmots.

Chaque programme est lui-même divisé en modules communiquant par des valeurs communes qui lui sont propres (COMMON).

La capacité mémoire de l'ensemble du simulateur, incluant le logiciel de base du constructeur (RTM), le moniteur temps réel spécifique à l'application, les programmes du poste de l'instructeur, ainsi que la mémoire supplémentaire prévue pour les éventuelles modifications et l'exécution de tâches différées exécutées pendant les temps libres, peut varier de 128 à 240 Kmots suivant les options et le langage retenus.

2.3 Cycle de calcul

Les tâches les plus urgentes doivent être exécutées toutes les 50 ms, cycle de calcul de base, et tous les programmes de simulation doivent avoir été exécutés au moins 2 fois par seconde.

3. PARAMETRES INFLUENCANT LE CHOIX DU FORTRAN

3.1 Format des données

3.1.1 Calculs scientifiques

Les valeurs utilisées sont des nombres réels ayant une partie entière et une partie fractionnaire.

Le FORTRAN traite ces nombres obligatoirement en virgule flottante. Aussi un argument souvent développé en faveur du FORTRAN, est l'amélioration de la précision des calculs grâce à la virgule flottante.

Ce raisonnement vient du fait que dans les simulateurs programmés en langage assembleur, les calculs sont effectués en virgule fixe afin d'optimiser le temps d'exécution des programmes, des instructions en virgule flottante performantes n'existant pas.

Les calculs en virgule fixe représentent une véritable difficulté pour le programmeur, les recadrages étant la source de nombreuses erreurs. Le format de 16 bits souvent utilisé dans les mini-calculateurs de la génération précédente, rendait critiques les problèmes de précision et obligeait souvent à faire des calculs en double précision.

Avec les calculateurs actuels, ayant un format de données sur 32 bits et des instructions en virgule flottante rapides, la programmation des calculs en format flottant avec le langage assembleur ne pose aucune difficulté.

La qualité de la simulation n'est donc pas améliorée par le FORTRAN, et en fait le langage assembleur laisse un plus grand choix dans le format des données.

En effet la virgule flottante n'a pas que des avantages dans un simulateur, car les entrées-sorties sont naturellement en virgule fixe, correspondant à des tensions électriques. Il se pose ainsi un problème de conversion Flottant/Fixe, Fixe/Flottant, coûteux en temps de calcul. Une manière de résoudre ce problème est de faire exécuter ces conversions par l'interface.

Notons également que, si les instructions câblées en FORTRAN sont relativement performantes, elles sont cependant nettement plus lentes que les opérations en virgule fixe.

3.1.2 Calcul logique

Compte tenu du grand nombre d'entrées-sorties logiques, correspondant à des interrupteurs et voyants dans la cabine de l'avion, chaque entrée ou sortie est représentée par un bit, l'ensemble des bits étant regroupés dans un mot afin d'utiliser au mieux les canaux d'entrées-sorties rapides.

Le langage assembleur est bien adapté au calcul logique sur bits et le programmeur expérimenté pourra optimiser certaines séquences de programme avec une disposition adéquate des bits dans les mots, ou par l'adressage indirect. Il pourra également tester des groupes de bits par une seule opération.

Le FORTRAN n'offre généralement pas la même souplesse de traitement du bit, en particulier dans le cas de tableaux de bits indicés, fréquents dans le problème de simulation de logique pour des systèmes doublés, triplés ou quadruplés.

En outre, les fonctions sur bit ne sont pas standards en FORTRAN et n'existent pas sur tous les compilateurs. L'identité des déclarations n'est donc pas assurée quand la possibilité existe.

Nous reverrons ce problème dans l'étude de la facilité d'écriture et du coefficient de foisonnement.

3.2 Facilité d'écriture

Il est habituel d'entendre ou de lire que l'avantage majeur d'un langage évolué sur le langage assembleur est la facilité d'écriture des programmes. C'est en fait sa raison d'être.

Le langage Assembleur est spécifique d'un calculateur, demande une connaissance du fonctionnement de ce dernier, et les erreurs de codage sont nombreuses et pas facilement détectables en dehors des erreurs de syntaxe. De plus, le programmeur doit avoir en tête les contraintes d'adressage et d'indexation.

Le programmeur passe difficilement d'un langage assembleur à un autre malgré une apparente facilité. Il veut généralement appliquer au nouveau calculateur des séquences particulièrement adaptées au précédent, et si le jeu d'instructions est très différent, le résultat sera mauvais.

Il faudra donc une réadaptation plus ou moins longue, et oublier un langage pour en utiliser un autre efficacement. Aussi l'utilisation simultanée de plusieurs calculateurs par un même programmeur à une influence néfaste sur la qualité des programmes.

Enfin beaucoup de langages Assembleur ne possèdent pas de directive permettant l'écriture aisée de nombre fractionnaire en virgule fixe.

Par contre l'utilisation de macro instructions en assembleur permet d'améliorer largement la facilité d'écriture, sans pénaliser la puissance du système.

Le FORTRAN est un langage universel, théoriquement standard et indépendant du calculateur utilisé.

Rares sont les calculateurs ne possèdant pas de compilateur FORTRAN, et presque tous les étudiants en sciences et techniques apprennent les bases de ce langage à l'école.

Cependant ce critère de choix en faveur du FORTRAN doit être modéré par le fait que pour améliorer les possibilités des compilateurs FORTRAN, les constructeurs développent des options non standards, et qu'un programme utilisant toutes les options, en particulier d'un FORTRAN dit "temps réel", d'un calculateur ne sera pas transportable sur un autre calculateur.

En outre si le critère d'efficacité du compilateur entre en jeu, et si le coefficient de foisonnement est critique, alors l'écriture d'un programme en FORTRAN devra suivre des règles strictes, différentes pour chaque calculateur, si on veut que le code généré soit acceptable.

On éliminera souvent hélas les séquences les plus agréables à écrire par la puissance de leurs possibilités.

Le programmeur, pour découvrir ces règles d'utilisation, que le constructeur se garde bien de communiquer, devra alors étudier le code généré par le compilateur, et donc connaître le langage Assembleur. Ainsi dans un système où la marge de puissance est critique, le programmeur pourra être amené à réécrire plusieurs fois un programme FORTRAN afin d'optimiser le code généré. Ce n'est qu'après plusieurs expériences qu'il pourra écrire en FORTRAN "réduit" un programme optimisé.

Le critère "temps réel", lié à des facteurs d'économie, diminue donc la facilité d'écriture FORTRAN, ce problème existant pour tous les langages évolués.

3.3 Coefficient de foisonnement

Un programme écrit en FORTRAN prend un nombre de mots mémoire et un temps d'exécution plus importants qu'un programme écrit en Assembleur. Si cette affirmation est qualitativement incontestable, la quantification d'un rapport d'efficacité est très difficile.

Nous appelons coefficient de foisonnement le rapport entre un chiffre (nombre de mots ou temps d'exécution) obtenu en FORTRAN et le correspondant en Assembleur.

Ce critère est important pour un simulateur de vol dont l'environnement temps réel conduit à un facteur temps d'exécution des programmes critique. L'expansion de la capacité mémoire peut sembler moins critique compte tenu du prix des mémoires actuel. Cependant, l'augmentation du volume mémoire diminue la fiabilité du système et peut amener à une organisation plus complexe compte tenu les problèmes d'adressage. De toute façon, il existe une relation directe entre le nombre de mots mémoire et le temps de calcul.

Lors de la conception d'un nouveau système en FORTRAN, à partir d'un système connu en Assembleur, le programmeur doit être capable d'évaluer le coefficient de foisonnement. Il utilise pour cela la technique du "benchmark".

On désigne sous ce terme un programme d'essai permettant de faire une évaluation d'un système informatique.

Il est bien difficile d'obtenir des chiffres significatifs du constructeur de calculateur, concernant l'efficacité du compilateur FORTRAN. En effet les résultats d'un "Benchmark" ne sont valables que pour des programmes similaires, et l'écriture d'un programme FORTRAN doit tenir compte du calculateur pour obtenir un code généré optimisé. Aussi un programme FORTRAN écrit par un constructeur pour son calculateur pourra donner des résultats remarquables dans un cas particulier, et des résultats très mauvais sur le calculateur du concurrent.
Peut être l'inverse pourra-t-il se produire pour un autre programme, ou simplement en écrivant le même programme avec une technique différente.

Aussi le "benchmark" universel n'existe pas, et le programmeur voulant évaluer un système doit écrire lui-même son programme, ce dernier devant être le plus représentatif du système définitif.

Pour être significatifs, les "benchmarks" doivent utiliser un grand nombre d'instructions, écrites sans intention préalable de démontrer l'efficacité ou l'inefficacité d'un compilateur donné.

Un exemple classique d'un mauvais "benchmark" FORTRAN est le suivant :

```
      DO   100   I  =  1,N
      Z (I) =  X (I) ** 2 - (A+B) * Y
  100 CONTINUE
```

Le programmeur aurait dû sortir le calcul de (A+B) * Y qui n'est pas indicé afin d'améliorer le temps de calcul.

Or certains compilateurs corrigent cette erreur et d'autres pas. La comparaison des temps d'exécution du "Benchmark" dans ce cas sera donc faussée.

L'utilisation de "Benchmark" pour comparer un langage évolué à un langage assembleur afin d'en déduire un coefficient de foisonnement est encore plus subtile.

De même qu'un programmeur connaissant bien les particularités d'un compilateur peut optimiser le code généré sur un calculateur particulier, un programmeur expérimenté en assembleur pourra optimiser plus ou moins une séquence de programmation au détriment de la facilité d'écriture, de mise au point et de modification.

Aussi les chiffres donnés pour des programmes de démonstration, ou de courts sous-programmes doivent être considérés avec prudence.

3.4 Mise au point des programmes et modifications

Un programme de simulation comporte deux niveaux de mise au point. Le premier consiste à éliminer les erreurs de codage et le deuxième à mettre au point la modélisation à l'aide des résultats fournis par le programme.

La première phase est importante pour un programme écrit en assembleur. Des erreurs de codage non éliminées pendant la première phase perturbent souvent la deuxième phase.

Les compilateurs éliminant la plupart des erreurs de syntaxe, la programmation FORTRAN permet une mise au point très rapide du premier niveau.

La technique utilisée pour la mise au point de la modélisation est la même en assembleur et en FORTRAN.

Cependant les temps de modifications et d'essais sont plus longs en FORTRAN dans la mesure où le programme doit être recompilé à chaque modification alors que le langage assembleur permet l'introduction de séquences provisoires sans assemblage. Cette possibilité est particulièrement appréciée pendant les tests en temps réel avec la cabine de l'avion.

Cependant la probabilité d'erreur par modification du code machine sans assemblage est assez grande et la mise à jour du programme source est quelquefois oubliée ou différente de la modification provisoire.

La mise au point de la modélisation en FORTRAN sera donc peut-être plus longue mais sera plus sûre.

3.5 Documentation

Dans un programme en langage Assembleur les commentaires se trouvent sur la même ligne que l'instruction.

Une instruction comportant peu d'informations, la place est suffisante pour les commentaires. Cependant pour assimiler la structure d'ensemble du programme, des organigrammes détaillés sont indispensables.

Les ordres FORTRAN sont suffisamment explicites pour qu'ils constituent eux-mêmes une documentation. Cependant la difficulté de compréhension n'est pas tant dans les ordres que dans la signification des symboles des paramètres. De nombreux symboles pouvant apparaître sur une même ligne, et les commentaires étant sur des lignes réservées à cet usage, un programme FORTRAN bien commenté comportera plus de lignes de commentaires que de lignes d'ordres.

Le programmeur devra faire un effort de mise en page pour que les ordres FORTRAN ne soient pas "noyés" dans les commentaires.

Les organigrammes accompagnant un programme FORTRAN peuvent être plus généraux que pour un programme Assembleur.

4. UTILISATION DU FORTRAN POUR UN SIMULATEUR D'AIRBUS

4.1 Introduction

Le simulateur AIRBUS n'est pas notre première expérience du FORTRAN mais c'est la plus complète concernant en particulier les problèmes de logique.

Nous avons utilisé ce langage principalement pour effectuer des études de simulation en centre de calcul, et pour réaliser des programmes utilitaires ou de maintenance. Par ailleurs, des simulateurs de centrales nucléaires sont réalisés partiellement en FORTRAN.

Le chapitre précédent tient compte de l'ensemble de notre expérience et des recherches effectuées sur le sujet. Dans ce chapitre nous examinons les critères vus précédemment pour le cas du simulateur d'Airbus.

4.2 Format des données

Tous les calculs mathématiques sont effectués en format flottant sur 32 bits (REAL), sauf certains calculs de navigation où la double précision s'est avérée nécessaire. Rappelons que sur le SEL 32 le format REAL est de la forme :
$X = F * 16^{E-64}$ où $1/16 < F < 1 - 16^{-6}$ et $-64 < (E-64) < 63$ F étant sur 24 bits et E sur 8 bits.

Pour des calculs et tests logiques, les formats bits et octets sont utilisés.

4.3 Facilité d'écriture

Le programmeur FORTRAN disposait d'un document d'analyse, du programme assembleur et de l'assistance du programmeur ayant écrit le programme assembleur.

Des règles de base liées aux problèmes de communication entre programmes ont été données :

- valeurs communes inter programmes dans un "COMMON DATA POOL".

- valeurs communes inter modules d'un programme dans un "COMMON" unique compilé avec chaque module.

- données communes logiques sur octets.

Aucune règle restrictive n'a été imposée au programmeur sous forme d'interdiction, considérant que l'avantage majeur d'un langage évolué est de pouvoir être écrit rapidement d'une manière naturelle.

Cependant un objectif a été fixé que le coefficient de foisonnement ne dépasse pas le chiffre de 1,2 retenu suite à l'exécution de "Benchmarks" particuliers et sur la base d'informations fournies par le constructeur du calculateur.

Des recommandations ont ainsi été faites :

- Eviter d'utiliser des calculs logiques sur bits et en particulier des tableaux de bits indicés, cas très fréquents dans les programmes en Assembleur.

- Effectuer le passage d'arguments à des sous-programmes par "COMMON".

Les programmes ont ainsi été écrits plus rapidement qu'en Assembleur, mais certains programmes de logique ont dû être écrits plusieurs fois afin de réduire le coefficient de foisonnement.

Les programmeurs interrogés sur leurs préférences quant à l'écriture en FORTRAN ou en Assembleur, ont généralement déclaré qu'ils préféraient le langage Assembleur pour les programmes de logique, et le FORTRAN pour les calculs mathématiques.

La difficulté d'écriture de programmes de logique est certainement due aux restrictions imposées concernant les ordres sur bits.

L'avantage du FORTRAN pour les calculs est principalement dû à la suppression des problèmes de cadrage.

Certains programmeurs considèrent qu'en développant des macro-instructions adaptées à leur problème, compte tenu de la répétitivité des séquences, la facilité d'écriture en Assembleur est comparable à celle du FORTRAN. C'est le cas en particulier de la simulation du pilote automatique.

Il est à noter, et ce commentaire est basé sur une grande expérience des Langages Assembleurs portant sur de nombreux calculateurs utilisés pendant les quinze dernières années, que le langage assembleur du SEL 32 est particulièrement facile à apprendre et à utiliser.

4.4 Coefficient de foisonnement

4.4.1 Introduction

La consigne donnée aux programmeurs était de réduire le plus possible le temps de calcul, au détriment éventuellement du nombre de mots mémoire.

Il est en effet plus facile d'augmenter la capacité mémoire que la puissance de traitement.

Cependant la mémoire d'un calculateur devant être limitée à 128 Kmots afin d'avoir un adressage direct sans pagination de la mémoire, la capacité mémoire ne doit pas être "gaspillée".

En moyenne les coefficients de foisonnement mémoire et temps de calcul sont à peu près équivalents et égaux à 1,45.

4.4.2 Programme de calcul

Le FORTRAN est bien adapté à l'écriture d'expressions mathématiques et le compilateur génère un code machine presque équivalent à celui écrit en langage Assembleur. Le coefficient de foisonnement se situe entre 1,05 et 1,10 pour la capacité mémoire, et vers 1,30 pour le temps de calcul.

Cette augmentation du temps de calcul est due aux instructions de traitement en virgule flottante.

Les sous-programmes de calculs standards tels que sinus, cosinus, racine carrée, etc..., ont été réécrits en Assembleur avec une précision inférieure aux sous-programmes FORTRAN SEL afin de réduire le temps de calcul.

Il en est de même des sous-programmes de calculs de fonctions d'une ou deux variables par interpolation linéaire, très utilisés dans les calculs aérodynamiques et moteurs.

Les tables de fonctions prennent deux fois plus de mots mémoire, les données étant sur demi-mot en Assembleur ce qui n'est pas possible en FORTRAN.

Les programmes effectuant uniquement des calculs sont rares dans un simulateur d'entraînement et représentent à peine 10 % de l'ensemble des programmes.

4.4.3 Programme de logique

Aucun programme n'effectue que des calculs de logique. Un grand nombre de programmes ont cependant une part prédominante de traitements logiques.

Ces programmes ont en moyenne des coefficients de foisonnement variant de 1,45 à 1,75 avec des exceptions pour des modules ayant des traitements de bits obligatoires. Ainsi un module d'affichage sur indicateurs numériques a un coefficient de foisonnement de 3 en temps de calcul.

Une des raisons de l'expansion du code généré, autre que celle de la manipulation de bits, est la restauration des registres à chaque branchement, très souvent difficile.

4.5 Mise au point des programmes et modifications

Le programmeur obtient très rapidement en FORTRAN un programme opérationnel.

La phase de mise au point de l'analyse en centre de calcul demande des moyens plus importants qu'en Assembleur.

Le programmeur souhaite pouvoir compiler son programme lui-même afin de tester rapidement une modification.

Il est alors utile, pour éviter les manipulations et les pertes de temps, d'avoir le fichier source sur disque et des allocations de mémoires centrales suffisantes pour faire une compilation en même temps que d'autres programmeurs mettent au point leur programme.

Dans l'état d'avancement du projet, il est trop tôt pour porter un jugement sur la mise au point en temps réel.

5. CONCLUSIONS

Un simulateur d'entraînement au pilotage programmé en langage FORTRAN sur SEL 32 doit avoir une puissance de calcul et un volume mémoire 50 % supérieurs au même simulateur programmé en langage Assembleur. Ce coefficient suppose que les programmes soient écrits avec un FORTRAN restreint, sans faire appel aux sous-programmes standards de la bibliothèque FORTRAN.

L'inconvénient majeur du FORTRAN dans ce type de système est donc la nécessité d'augmenter la puissance du système informatique de manière relativement importante. Cet inconvénient n'est que partiellement compensé par une facilité de programmation moins évidente que le laisserait penser l'utilisation courante en centre de calcul scientifique.

Le constructeur du calculateur, conscient de ce problème, propose actuellement un "accélérateur scientifique" permettant d'améliorer de manière importante les temps d'exécution des sous-programmes de la bibliothèque FORTRAN.

L'avantage majeur est l'universalité du langage. Il semble que cet avantage soit intéressant surtout pour l'utilisateur qui souhaite modifier les programmes de manière assez importante.

SIMULATION OF A NIGHT VISION SYSTEM FOR LOW LEVEL HELICOPTER OPERATIONS

by

Dr J. N. Barrett

Royal Aircraft Establishment, Farnborough, Hampshire, UK

SUMMARY

Extensive research is being carried out in the United Kingdom aimed at improving the all weather operation of helicopters. One facet of this work is the development of night vision piloting aids to enable helicopters to operate at low altitude by night. This paper describes an experiment which explored the problems and possibilities of a helmet mounted display for such helicopter night piloting tasks, using real time simulation techniques.

The paper describes the development of the helicopter simulation, and how the various components of the proposed night vision system were modelled and incorporated into the simulation, to provide an accurate reproduction of the proposed airborne system, and an acceptable task for the pilot to perform. The paper discusses the experimental design for the trials and how the limitations of the simulation were taken into account. Finally, the results of the work are described and how these have helped from the basis for the actual airborne system.

1 INTRODUCTION

The helicopter in its military role has the ability to undertake many types of operational mission. This inherent flexibility of operation, which is far greater than conventional fixed wing aircraft, depends to a large degree on the pilot's ability to maintain good ground contact in order to recognise and identify features. When this ground contact is prevented by low scene illumination or poor visibility, the mission capability is removed particularly for those missions involving low level flight at or below the local obstacle clearance level. So to make helicopter poor weather or night operations possible, it is not solely a question of providing suitably processed flight information, as is the case for some types of fixed wing aircraft. Rather means must be devised to give the pilot some direct or indirect view of the outside world to re-establish ground contact and retain the mission capability.

Some of the night vision systems currently proposed require little or no aircraft modifications, and because of this they can be assessed in an airborne environment at a reasonably low cost. Other systems are much more complex however, and to flight test an unproven design may prove to be very expensive and also very wasteful, if the original concept had a major design weakness. It is in this situation that the flight simulator can play a very important role allowing as it does airborne systems to be evaluated in a controlled environment for a relatively low cost.

This paper describes a night vision system evaluation and development in a research simulator where complexity was kept to an absolute minimum commensurate with ensuring an adequate test environment. The night vision concept assessed was a visually coupled system. In the airborne system this would comprise a platform mounted sensor, a helmet mounted display which presents the sensor output to the pilot, and a head sighting system whose head angle outputs continuously direct the sensor platform to the pilot's line of sight. In addition the airborne system requires a waveform generator to provide symbolic flight information to assist in pilot knowledge of aircraft attitude, speed, and height etc and also to maintain orientation when flying on the helmet display.

The simulator basically consisted of a cockpit, digital computer and visual flight attachment. The only airborne components used in the trials were the helmet display and head sighting system. A ground based waveform generator was used to provide overlay flight information and the functions of the platform and sensor were performed by the visual flight attachment. These latter components are by far the most expensive and complex of the airborne system, and this was where the major cost savings were made, apart from the basic trade off of simulator flying hours against flight hours.

The great advantage of the visually coupled system over alternative forms of night vision system such as a fixed forward looking sensor driving a head down display, is that it provides the pilot with a look round capability. It also has the added advantage that the image of the outside world can be focussed at infinity and a 1:1 magnification is possible whereas a panel mounted display normally presents a demagnified image and cannot easily be collimated. Passive night goggles, which are self-contained image intensifiers mounted on the pilot's helmet, also provide a look round facility, but their current capability and long term performance development are ultimately limited by the sensor size. The effective aperture and therefore night vision performance of the sensor in the visually coupled system is only limited by the size and total payload constraints of the platform and vehicle.

The most significant human factor problem of the visually coupled system is caused by the present design monocular viewing systems. This was the area where the flight simulation was most effective in allowing an assessment of binocular rivalry and disorientation. Other system characteristics investigated were platform slew rate and overlay flight information requirements.

2 OBJECTIVES

The objectives of the simulation experiment were to isolate potential problems and develop solutions appropriate to flying a helicopter by night at low level, using the visually coupled system as the piloting aid. The type of problems envisaged are:-

(a) disorientation when looking off track caused by the limited outside world peripheral cues and the monocular display;

(b) asymmetric weight problems due to the monocular display being mounted on the right-hand side of the helmet;

(c) cable drag resulting in restricted head movement and additionally any other equipment use problems.

It was also a specific objective of the trial to establish a suitable symbolic overlay display of flight information to assist in the flying task and maintaining orientation and to determine the required sensor slew rate.

A final significant area, where the flexibility of the simulator was used to the full, was in the assessment of the level of aircraft stabilisation required to produce an acceptable pilot workload when flying at low level.

3 VISUALLY COUPLED NIGHT VISION SYSTEM

In the normal airborne installation, the visually coupled system comprises a head sighting system coupled to a slewable platform in the nose of the aircraft. Within this platform a suitable night vision sensor is mounted, either low light television (LLTV) or forward looking infra-red (FLIR). The sighting system measures pilot head angular orientation in elevation and azimuth, and these signals are fed to the platform so that the night vision sensor is looked to the pilot's line of sight. The sensor output is fed to a helmet mounted display which presents to the pilot a collimated scene image at unity magnification. As the pilot moves his head, the platform follows (up to the gimbal limits) giving a continuous view of the outside world, as if the pilot were looking through the windscreen. Typically, the system provides an instantaneous field of view of 40° with an area of coverage from the platform of $\pm 100^\circ$ in azimuth and $+20^\circ$ to -110° in elevation. Because of the elevation coverage, the pilot can actually "look through the floor" of the helicopter vertically downwards. Provided potential disorientation effects can be overcome, the visual coverage at night is much greater than with passive night goggles. This can be very advantageous during search and rescue missions or when landing in a restricted site.

4 HELICOPTER SIMULATION

The assessment of the helmet mounted display system was carried out using a fixed base digital simulation of the Lynx helicopter (WG 13). The mathematical model was based on the full flight equations of a Lynx helicopter developed by Westlands. Although these were originally written for an analogue machine they were found to be perfectly adequate for the present trials after translation into suitable digital machine language. The digital computer used was the Redifon 2000A 24 bit machine which has an iteration rate of 18 Hz. The flight programme only occupied some 2000 words of core storage, but gave a full six degrees of freedom simulation from the hover up to 160 kn. The digital computer was coupled to an analogue to digital, and digital to analogue input/output interface system which handled stick and collective inputs etc, and provided output drives to a visual outside world presentation and the flight instrument displays.

4.1 Cockpit

The simulator cockpit shown in Fig 1 was a fixed base representative wooden mock-up of the front of the Lynx helicopter. This was sited in an area which could be darkened to simulate night conditions, and which was isolated from the computer and control room. A representative intercom system was used to communicate with the pilot whilst he was flying the various tasks.

The subject pilot flew the simulator using representative cyclic, collective and rudder controls. A pitch and roll trimming facility was provided by means of a switch on the stick top. Because the cyclic control was very simple comprising a spring feel system with potentiometer pick-offs, operating the trim switch did not move the stick as in the normal aircraft, but simply added a small digital increment to the existing control input in the programme for each iteration of the computer. This was a slight limitation since the cockpit was not fitted with trim gauges, and in consequence the pilot could 'trim' the helicopter to one end of the control run and run out of control authority without realising it.

The only instrumentation in the cockpit was a 0.28m diagonal television monitor which presented the simulated outside world terrain image, together with superimposed flight information provided by a programmable symbol generator. This head down display replaced the normal conventional cockpit instruments, this meant that a study could not be

made of the effect on performance, when using the visually coupled system and attempting to read the head down instruments.

Two press to make switches were installed in the central cockpit console for a fixed route navigation task described in section 6.2. One was to select a new waypoint, the other to display, on the overlay flight information, the required heading to steer to the next way point. (The overlay display used at the start of the trial is described in section 6 and its subsequent development described in section 7.3

4.2 Visual flight system

The simulated outside world was provided by a closed circuit television system which comprised a camera viewing a contoured modelled belt, scaled at 3000:1. Fig 2 is a photograph of the belt, and camera gantry system. This scaling was just adequate to provide realistic contouring and reasonable simulation of airfields, towns, woods etc. The belt was 11.5 m long by 3 m wide, providing a usable scaled area for flight of 34.5 km by 9 km, but because the belt was driven in a continuous loop, a numerous number of possible flight paths over different terrain were possible. Fig 3 shows a map of the terrain and the waypoints and navigation route.

Helicopter forward velocity was represented by a combination of belt speed and camera lateral velocity. Height was represented by camera displacement above the terrain. The camera viewed the modelled terrain via an optical probe, which reproduced aircraft pitch, roll and heading changes. The inputs to the various angular and linear servo systems was provided by ground axis transformation algorithms in the computer programme, via the digital to analogue converter interfaces.

Because of the mechanical arrangement of the camera gantry and belt, the available heading sector available for flight was only ±90°. This meant that complete circuits could not be flown and that large off centre-track heading changes could not be maintained very long without the camera reaching the side of the belt. Due to the design of the camera optical probe, there was a limited full scale deflection of ±20° of bank angle and ±25° of elevation angle. The restriction in elevation angle prevented an assessment of the "through the floor" capability envisaged in the airborne visually coupled system, but this did seriously detract from the value of the experiment.

The closed circuit television camera had a zoom lens arrangement allowing outside world fields of view from 60° to 15°. For the present trials, this system was adjusted to give a field of view of 40° in azimuth by 30° in elevation on both the panel mounted and helmet mounted displays, since this had been found from previous trials to provide an acceptable compromise of field of view and resolution for the low level piloting task. At the normal viewing distance the panel mounted monitor only subtended 17.5° by 13° at the pilot's eyes, giving an image magnification of 0.44. When flying on the helmet display the pilot had a full 1:1 image magnification, which proved to be of some advantage during the trials.

Despite the long depth of focus provided by the f/64 relative aperture of the camera optics, an additional automatic focus facility was built into the system. This was driven by aircraft height to keep the middle foreground of the image in focus at all times.

One particular feature of the simulator, which assisted greatly in the realism of the flying task was the 'radio height' system. This was achieved by measuring the height of the terrain on a grid system of 5 cm squares over the whole terrain. Each height value, together with its X and Y position, was then stored in the digital computer. Using the X and Y position feedback signals from the belt and correlating these with the stored grid, the computer was able to output a continuous radio height signal, wherever the helicopter was over the terrain.

5 HELMET MOUNTED DISPLAY

The only parts of the normal airborne system which were used in the simulation were the head sighting unit and helmet mounted display and associated drives. The action of the platform mounted sensor was simulated by driving the camera and optical probe of the simulated outside world in a suitable manner as described below.

The head sighting system and helmet display were manufactured by Honeywell and are illustrated in Fig 1 in position in the cockpit. The head sighting system basically consisted of two sensor surveying units (SSU) mounted each side of the pilot's head which produced horizontal fan shaped infra beams, which swept in an arc downwards through the cockpit. These beams were detected by a pair of photo-transistors mounted horizontally with a separation of 150 mm on one side of the helmet, together with a corresponding pair on the other side. Each SSU produced two synchronised infra-red fans separated vertically by about 100 mm. The intersection of these beams with the phototransistors generated pulses whose timing relative to the start of the scan was used to calculate the helmet attitude relative to the SSU. Axis transformation calculations were then performed to convert the SSU referred angles to head elevation and azimuth angles relative to the cockpit. In the simulator, a further stage of axis transformation had to be performed to convert these cockpit or aircraft axes angles to ground axes. The ground referred head azimuth and elevation angles were then simply added to the normal aircraft heading and pitch angles respectively, and then fed to the outside world camera optical probe. Whatever the attitude of the aircraft, the optical probe responded as if it were a two degree of freedom sensor platform mounted .. the aircraft. With the camera output

presented on the Honeywell helmet mounted display, the pilot had an instantaneous field of view of 40° of the outside world at unity magnification, focussed to infinity.

The helmet display was mounted horizontally along the bottom edge of the right hand side of the helmet. The 25mm CRT contained within the unit was viewed via in-line collimating optics and a reflector plate as illustrated in Fig 4. As with all current designs this helmet mounted display was monocular, the outside world image only being viewed by the pilot's right eye. This not only gave rise to asymmetric weight problems, but also produced severe operating problems as discussed later.

5.1 Overlay flight information

It was anticipated prior to the start of the trials, that it would be extremely advantageous for the pilot to have some basic flight information superimposed on his forward view of the terrain; not only to assist in the basic piloting task, but also to aid orientation when looking off-track with the helmet display. The basic overlay flight information format investigated during the trial is shown in Fig 5. Pitch and roll attitude were presented in the centre of the display by an artificial horizon referenced to an aircraft symbol with pitch and roll scales. Radio height in feet and speed in knots were indicated as digital readouts at the bottom right and left of the display, respectively. Aircraft heading was shown as a horizontal linear tape in 10° increments along the bottom of the display, and vertical speed was presented at the right hand side by means of a thermometer read against a vertical scale, where each index from the datum represented an increment of 250 ft/min. The final primary flight symbol presented was sideforce, indicated by the displacement of an ellipse moving against the heading marker.

As described in the following section, the pilot was given a navigation task as a part of the trial, and to ease the total workload, the navigation information was also presented on the helmet mounted display as shown in Fig 5. This consisted of the number of the waypoint currently being approached, presented at the top left of the display and immediately below this the range, in nautical miles, from the helicopters present position to this waypoint. Additionally, a heading to steer bug driven horizontally on the heading tape, gave a continuously computed readout of the heading to steer to reach the waypoint from the helicopter's present position.

The drives to this navigation system were produced by an especially written software programme which sought to emulate the function of an airborne Doppler navigation computer. The programme only occupied some 300 machine instructions and relied for its operation on the knowledge of aircraft present position in X and Y, from the belt and camera feedback system, and the X and Y positions of the 18 different waypoints. Knowing the waypoint selected, a simple geometric algorithm was used to calculate the range and bearing of that waypoint from the aircraft present position, and output these signals to the waveform generator.

The overlay display was produced by a cursive programmable waveform generator which had a 1000 word 24 bit programme store and a 1000 word 8 bit symbol store. The primary display symbol drives were provided by the main computer via a digital to analogue/analogue to digital interface unit. (Direct digital drive was not possible in this case because of incompatibilities in the digital word structure between the two machines.) The main programme capability in the waveform generator was used to perform datum and scaling functions and to call up the required characters from the symbol store. The output from the waveform generator was presented on a cursive head down display which was viewed by a nuvicon television camera to provide a scan converted raster output for mixing with the video signal from the model terrain camera. This composite mixed video was then fed both to the head down monitor in the cockpit and the helmet mounted display.

6 EXPERIMENTAL DESIGN

Due to the limitations of the simulator, (ie lack of motion cues and limited modelling of the normal aircraft instruments), it was realised that the successful outcome of the trials depended to a great extent on the experimental design adopted. To minimise the effect of simulator limitations a comparison exercise was carried out between the head down display (for which flight trial results were already known) and the helmet mounted system. Additionally, great care was taken to ensure that the pilots were thoroughly familiar with the simulator and the task to be performed, before the trials started. The subsections below describe in detail the techniques adopted and the measurements taken to provide a sound basis for any subsequent trials of the equipment.

6.1 Pilots' briefing and familiarisation

Prior to the experiment, each participating pilot was given a written brief which described the helmet mounted display and overlay data, and gave an outline of the experiment, its objectives and an indication of what each task entailed. They were also asked to study a comprehensive questionnaire, to be completed after the experiment, given a copy of the navigation route (Fig 3) and a Cooper Harper rating sheet shown in Fig 6.

Initially a period of time was spent in allowing each pilot to become familiar with the equipment. This involved flying the helicopter on the head down display with and without the look round facility. The pilots participating in the experiment had varied flying experience and, of course, different learning curves. This created the difficulty of deciding how much practice time each pilot required to ensure that all of them were at the same level of performance before undertaking the tasks. As a simple measure of task

proficiency each pilot had to keep his height over the terrain to between 150 ft and 250 ft agl for 5 minutes, when flying the navigation task.

6.2 Piloting tasks

There were two major tasks that the pilots were given to fly. The first was a reconnaissance exercise and involved flying the specified route shown in Fig 3, over the 18 waypoints using the navigation information presented on the overlay display. In order to make each waypoint readily identifiable a specific ground feature was modelled at each one. A list of these is shown on the map in Fig 3.

To simulate a reconnaissance operation the pilot was required to spot and verbally identify as many off-track targets, *ie* simulated tanks, as possible. By tape recording the tasks, a scoring could be taken of the number identified.

The second task was a simulated anti-tank operation, which was to locate and then fly to a specified number of tanks in as short a time as possible. This simulated a target search operation with no defined route. The positions of the tanks for both operations, are shown in Fig 7. This information was not, however, supplied to the pilots, prior to the experiment. The purpose of both tasks was to make the pilot look off-track, so that a study of the helmet mounted display in its major role could be made. The 3000 to 1 scaling of the terrain model caused great problems in the modelling of the tanks. Tanks of the required scaling were so small, that it was not possible to make them with sufficient detail to allow them to be identified when flying over the terrain. To overcome this problem, the tanks were made double size to ensure that they could be positively identified. Although this reduced the authenticity of the trial, it was felt to be an acceptable procedure since it in no way invalidated the comparison between the head down and helmet mounted displays. Both tasks were flown in the height range from 150 ft to 250 ft using the head down display, the helmet display without the look round facility (*ie* simulating a fixed forward sensor) and the helmet display with the look round facility.

By processing six pilots at a time, a 6 × 6 latin square sequence could be used on the tasks to be performed. This ensured that residual learning effects and any biases in the results caused by performing the tasks in a constant specific order, were minimised.

6.3 Recording and analysis of trials results

This experiment was intended to be the first in a series of trials to study visually coupled systems. As such, it was felt that a primarily subjective assessment of the helmet mounted display would give most feedback, provided that this was sought in the most efficient way. More objective trials could then be staged which would concentrate on the important areas highlighted by these initial results. To achieve this feedback, a structured questionnaire was produced which sought pilot opinion on all aspects of the system. Although many of the questions in this were multiple choice, the pilot was encouraged to add additional comments to amplify his answers.

In order to quantify the difficulty of each task, the pilots were asked to apply a Cooper Harper rating to each one (Fig 6). In this evaluation approach, which was originally developed to assess aircraft handling qualities, a pilot selects one of ten categories of system acceptability, which most nearly describes his own view. This provides a rapid assessment technique which can be equally applied to display system selection.

7 ANALYSIS AND DISCUSSION OF RESULTS

Most of the results discussed below were obtained from the pilots' questionnaires and are set down in the sequence used for debriefing, starting with the simulation and moving on to the individual tasks and then to the equipment itself.

7.1 Flight simulation

All participating pilots were unanimous in the view that the flight simulator was adequate for the display system comparison task. There were, however, a number of deficiencies which detracted from the realism of the system, and which they felt needed improvement.

In terms of the handling qualities, it was found initially that changes in collective pitch produced too large a change in longitudinal aircraft pitch, and that the rolling moment produced by sideslip was far too small. Once these cross-coupling terms were modified, the responses of the vehicle to collective and cyclic control inputs were felt to be reasonably representative of a Lynx type helicopter.

In terms of agility, there was found to be reduced response of vertical speed to aft cyclic inputs at speeds below 100 kn compared with the actual aircraft. This meant that when approaching rising ground both collective and cyclic inputs had to be made in order to crest a hill, and this imposed an additional pilot workload, which would not be present in the real aircraft.

The other important factor which contributed to the difficulty of the general handling task was the lack of a representative trimming system. As discussed in

section 4.1, stick trim signals were added directly to the software control input, rather than by moving the stick. Although this was believed to be a limitation, it did not seriously undermine the value of the experiment as will become apparent from the results obtained from the trials.

The absence of other normal flight cues such as motion, noise and vibration inevitably detracted from the realism and increased the task difficulty to some extent, by causing the pilots to over-control initially, due to the lack of vestibular phase advance information. Overall, however, it was felt that the flight simulation was an adequate assessment medium for the comparison exercise, especially since the experiment was aimed at assessing concepts and establishing principles, rather than obtaining precise quantitative data.

The only other significant problem related to the simulation, highlighted during the trials was the lack of texture in the image from the outside world camera. (Texture in this case means rocks, grass, small bushes etc.) Because of the 3000:1 scaling the reproduction of such detail was almost impossible, and since a pilot normally relies on such details to accurately gauge aircraft height, more reliance had to be placed on the overlay flight information than would normally be the case. The problem was particularly noticeable when flying towards rising ground, and was further compounded by the fact that the immediate foreground tended to go out of focus, due to the close focus limitation of the visual system.

Although these criticisms were perfectly valid when applied to a simulation which sought to accurately reproduce the outside world, lack of texture, *ie* lack of ground feature resolution, is frequently a characteristic of night vision sensors, especially those providing a large azimuth field of view. Thus in this particular instance, the lack of ground feature resolution made the simulation to some degree more representative of the actual airborne system.

In general, the pilots found the reconnaissance and anti-tank tasks both motivating and representative of an operational task. Some problems were experienced in the latter stages of the navigation task, due to the waypoints being too close together and requiring large heading changes to go from one to the other. The other significant factors, which the pilots felt affected their performance were learning curve and fatigue. The criteria adopted for determining equal proficiency did not guarantee that all pilots had surmounted the learning curve. Because of this, some felt that more practice time would have been beneficial. On the other hand the total task was found to be very fatiguing, so that in many instances more practice time would have meant that the pilots were becoming tired, before they had even started the proper experiment.

7.2 Display comparison

In the questionnaire the subject pilots were asked to comment on a number of issues which related to the ease or difficulty of performing the set tasks using the helmet mounted display compared with the head down display.

Without the head sighting system in operation, the helmet display presented the same image as the head down display at all times. In comparing these two concepts, the pilots generally agreed that perceptually, both forms of display gave reasonably adequate height and distance cues. In isolation, the helmet display was preferred, because of its collimated 1:1 image which was much more natural to view than the head down display, where the image magnification was only 0.44. This preference was off-set overall by two significant factors; firstly, that the helmet display was monocular, which meant that totally disparate information in two different focal planes was presented to each eye, and secondly that there were occasional problems obtaining a sharp in-focus image which caused additional image resolution loss. The implications of these factors are discussed more fully in section 7.6.

With the head sighting system in operation the pilots found that the problems in the piloting and navigation task caused by the fixed narrow field of view were removed. It was possible to look into a turn before executing it, which improved with confidence, and once fully familiarised, more ground features could be used for navigation. When approaching a way point with the aircraft off track, for example, the look round facility enabled it to be easily spotted and held. With a fixed forward view, the particular ground feature could be lost completely, and in the actual airborne system a circuit would be required to relocate it.

With the head sighting system coupled to the simulated platform, the first major aspect which was discovered was that platform slew rates and accelerations were critical, if pilot orientation was to be maintained. In the simulator, platform motion was simulated by the optical servo system of the closed circuit television system, as described in section 5. The response of this servo could be easily altered to represent different platform responses. It was found that in order to prevent perceivable lag the platform required a slew capability of 120°/s from start to stop and had to be critically damped to prevent overshoot or undershoot. To meet this specification the platform required an angular acceleration capability of 900°-1000°/s^2.

When system lags were present, the pilot was forced to reduce his normal head rotation rate to keep the platform in step, and this not only added to the general task level, but prevented the pilot identifying targets of opportunity. This problem was highlighted when flying at very low level, since small undetected descent rates could

quickly increase, whilst the pilot was looking off-track, resulting at best in large uncontrolled collective inputs, and at worse in a crash. Even with the system optimised, where platform lag for an off-axis glance at 90° was no more than 0.1 s, there was a tendency for the pilot to instinctively increase height due to the lack of peripheral vision. Although this problem reduced with familiarisation, it was not minimised until the overlay symbology was modified as described below.

Another important requirement established whilst determining the platform characteristics, was the need for inner loop stabilisation on the helicopter. The simulation was originally set up with a simple rate damping system. With the relatively low degree of augmentation that this provided, the pilot could easily induce an unintentional pitching or rolling moment whilst looking off to the left or right. This problem was further compounded by the lack of motion cues or peripheral vision.

This was one area where the flexibility of the simulator was fully exploited, and it was found that the provision of an attitude trim term in the stabiliser control laws minimised the problem, and gave the pilot confidence to look off track more frequently. Although this may have also been solved by providing a continuous read-out of attitude wherever the pilot looked, this was found not to be acceptable as discussed in the next section.

Operationally, the pilot would have the motion cues not present in the simulator, but would not have normal peripheral vision when using the helmet display. Although it would need confirmation in an airborne trial, it is believed that an attitude stabilisation system on the helicopter would be mandatory when flying on the helmet mounted display at low level, in order to maintain an acceptable level of task difficulty.

7.3 Overlay flight information

Apart from platform head following rates another source of disorientation when using the visually coupled system was that the pilots had initial difficulty in resolving the difference between aircraft heading changes and head azimuth movements, since both produced the same effect to the image presented to the right eye. In addition when looking far off axis, although the inside of the cockpit could be seen by the left eye, the concentration on the display image was such that the pilot would be unsure which position to return to, to establish the helicopter attitude. When the overlay flight information was added, (as shown in Fig 5) this resolved some of the problems, but there then arose the question of whether the flight information should move with the head, or remain boresighted to the cockpit in some manner. It was quickly established that the latter procedure minimised any disorientation effects. Allowing the flight information to move with the head overcame the objection described above, of not knowing the aircraft attitude when looking off to the side, but compounded the disorientation effect.

To implement the cockpit stabilised overlay display, the head offset angles in azimuth and elevation were used to drive the overlay information across the CRT face of the helmet display to correspond one for one in angular subtense to the offset of the optical servo on the camera. To prevent the overlay information disappearing off the CRT for large head offsets, the drive signals were limited so that one edge of the flight information could always be seen. In this way the pilot always knew in which direction to move his head to re-establish the boresight. The only refinement made to this concept during the course of the trials was that the aircraft radio height was not driven in this way, so that it remained in the same position in the pilot's instantaneous field of view of the CRT. With this height readout always present, the pilot knew immediately if the ground clearance was reducing when looking to the side.

In general, the content and form of presentation of the overlay display was liked by the pilots. The digital readouts for speed and height could be easily read, although they lacked trend information. Although not important for the speed readout, it was suggested that a counter pointer height presentation would improve rapid appreciation of changes in clearance height. The incorporation of the navigation information on the display did not give rise to any scan problems. In fact, it was agreed that the total format gave the pilot all the continuous information needed to fly the task.

7.4 Helmet mounting

The mounting of the helmet display along the right hand side of the helmet gave rise to an asymmetric weight problem. Although the unit was fitted just below the head centre of gravity to reduce its effective moment, it still tended to roll the pilot's head to the right. The compensatory muscle power needed to hold the head upright produced slight neck ache in some pilots after an hour's sortie. In a separate experiment it was found that compensating weights on the left side of the helmet improved wearing comfort considerably, without increasing total head inertia to the point where rapid azimuth movements became difficult. Another problem which affected performance was cable drag. Apart from the normal earphone and throat microphone cable, the head sighting and helmet display drive cables ran from the back of the helmet to their respective drive electronics. To prevent any significant restriction on normal head movements, the cable weight was fully supported by rubber straps fixed to the cabin roof. Operationally this may be feasible, provided the design includes a provision for rapid release in an emergency situation.

7.5 Ease of use

In order to minimise the weight of the helmet display, the size of the display objective lens, intermediate lenses and combiner glass were kept as small as possible consistent with the 40° field of view requirement. It was found in practice, however, that the very small image exit pupil and eye relief that the design philosophy produced, made it very difficult to adjust the display on the helmet, for particular subject pilots, to achieve the full field of view without vignetting. This posed particular problems for the subject pilots who wore glasses, most of whom were unable to establish a satisfactory adjustment. The criticality of this optical design would obviously cause serious problems when the helmet display was used with any form of chemical or biological defence mask, or under normal helicopter vibration conditions. It should be stated that the unit tested was early generation equipment, and that more recent displays have a larger exit pupil and eye relief. Nonetheless, to achieve a totally acceptable solution requires an optical design where the element nearest the eye has some optical power. One way of achieving this is to use the helmet visor, as this optical element acting as a holographic lens.

7.6 Binocular rivalry

Helmet sighting systems which inject weapon or flight data into the right eye have been in use for some considerable time with great success. In this case, both eyes can see the outside world and because the disparate flight data into the right eye is a relatively small proportion of the total field of view and consists of low spatial frequency information, the brain accepts this without difficulty. This is not the case for the visually coupled system, however, where totally disparate information is fed to the foveal areas of each eye. This situation gives rise to a physiological effect called binocular rivalry which proved to be the most significant problem found during the simulator trial. In normal operational flying the pilot would be expected to view the image of the outside world with the right eye and then switch his mental attention to the left eye, when anything needed to be monitored in the cockpit. In the simulator, the cockpit was darkened to simulate night conditions and the display set to comfortable viewing brightness of 2 to 3 ft lamberts. After a certain period (which varied greatly from a few minutes to half an hour, depending on the subject), the pilot found it more and more difficult to concentrate on the outside world as the scene in the left eye would keep breaking into his attention. The only way to stop this effect, once started, was for the pilot to shut his left eye. By experimentation, it was found that equalising the light level into each eye caused the rivalry problem to occur fairly soon after the start of the flight and the pilot would be constantly distracted by the left eye scene resulting in severe pilot fatigue after a half hour sortie. If the light level into the left eye was reduced to a minimum by using a darkened visor with a patch over the foveal region, this increased the time to the onset of the rivalry problem, but then when it did occur it was more dramatic, causing the outside world information into the right eye to be lost temporarily. Operationally, at low level by night this could be disastrous.

It was concluded overall from the experiment, that the visually coupled system was viable provided that a bi-ocular or binocular viewing system could be developed to overcome this rivalry problem.

The Cooper Harper ratings (Fig 6) applied to the system acceptability, ranged from a figure of 6 (system has very objectionable but tolerable deficiencies) up to 8 (system has major deficiencies). In terms of demands on the pilot this meant at best that adequate performance requires extensive pilot compensation, to at worse considerable pilot compensation is required to retain control. When commenting on these figures, the pilots felt that they could be halved to 3 or 4 if a binocular viewing system was developed, and a higher level of stabilisation was incorporated into the simulated vehicle, to minimise aircraft handling difficulties when looking off-track.

8 CONCLUSIONS

The results of the trials on the visually coupled system described in this paper have adequately demonstrated the viability of using an unsophisticated, relatively low cost flight simulator, without representative motion or feel characteristics to determine the limitations and physiological and psychological problems of a complex avionics system. Further, the simulator trials have demonstrated the advantages of the visually coupled system and established the desirable system performance and human factors interface with the pilot.

It is believed that a simulation medium of this nature, where the system could be dynamically tested albeit crudely, revealed a wealth of information which could not have been established other than by way of extensive flight trials. In addition, the simulation allowed a large number of subject pilots to be exposed to the system, which is not usually the case with flight trials, where pilot participation is restricted due to specialist nature of the experimental vehicle and system, and the prohibitive cost of flying hours required to give each participant adequate exposure to the system.

Finally, since the simulator assessment provided an outline specification for the most expensive airborne piece of equipment viz the sensor platform, it provided an essential link in the system development from the design stage to flight trials, which if omitted could result at best in gross over or under engineering in this area, and at worse in major design faults being included which could prevent any useful results being obtained. In terms of cost saving, these factors alone justify the whole of the interim ground assessment.

Turning to the results obtained in this present assessment, it is believed that the trials have demonstrated the feasibility of the visually coupled system for piloting a helicopter at low level by night. It is concluded that the main advantage of the system is that it provides the pilot with a complete look round capability, where the area of coverage is dictated solely by the platform degrees of freedom. Particular conclusions on the present performance are as follows:-

(a) to maintain pilot orientation the platform head following lag must be minimised, and in addition cockpit boresighted overlay flight information presented on the helmet display image;

(b) The optical design should be improved to provide much greater display image eye relief and exit pupil, to cater for pilots with glasses and other forms of head protection gear. In addition, the asymmetric weight problem caused by the helmet display on the helmet, should be overcome by balance weights initially and in the long term by redesigning the unit to give a better weight distribution;

(c) the present monocular system gives rise to binocular rivalry which could produce serious flight safety problems when operating at low level. The development of a binocular or bi-ocular viewing system is therefore essential if the visually coupled system is to be operationally viable;

(d) the basic aircraft handling qualities required to provide an acceptable task level for the pilot when flying on the helmet display should be such that pilot compensation is not a factor in achieving desired performance. In practical terms, this would mean at least a low authority attitude stabilisation system in the pitch and roll axes.

9 ACKNOWLEDGMENTS

The Honeywell helmet display and sighting system used in these simulator trials were loaned to RAE Farnborough, by the Aeromedical Research Laboratories (AMRL), Wright Patterson AFB, USA, under the terms of an Aircraft Standardisation Coordination Committee Test Project Agreement 654161. The author wishes to express his gratitude to Mr T.A. Furness of AMRL, the Deputy Project Leader for permission to publish this interim paper on the results obtained with this system.

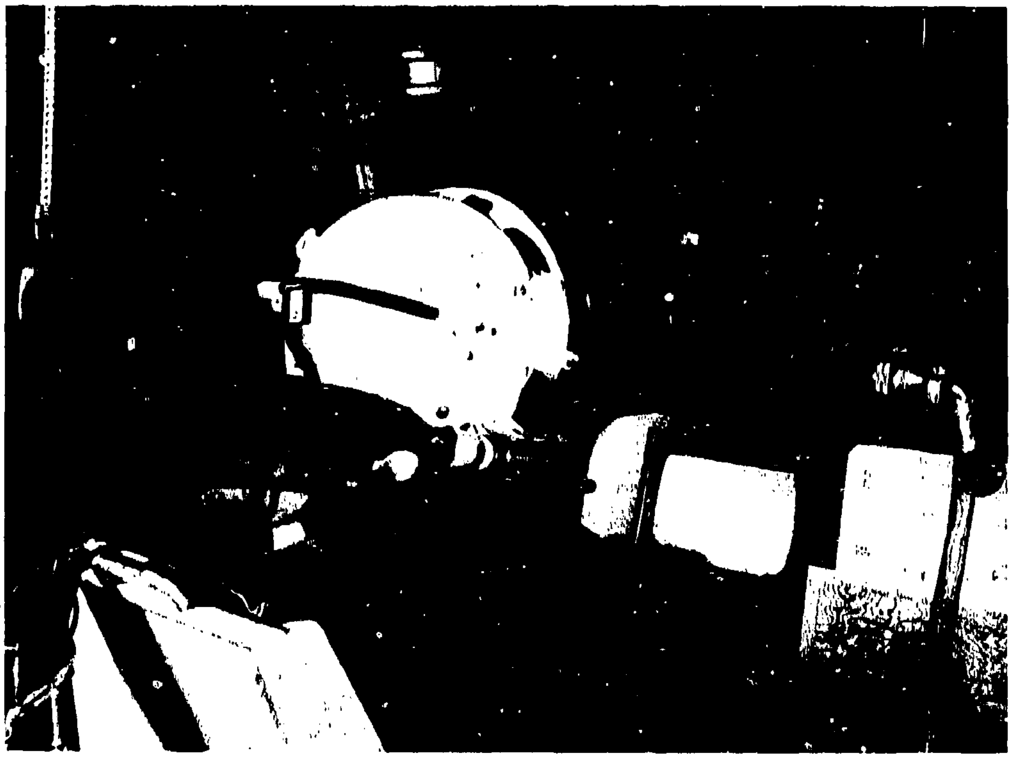


Fig 1 Simulator cockpit showing helmet mounted display, head sighting units and head down monitor

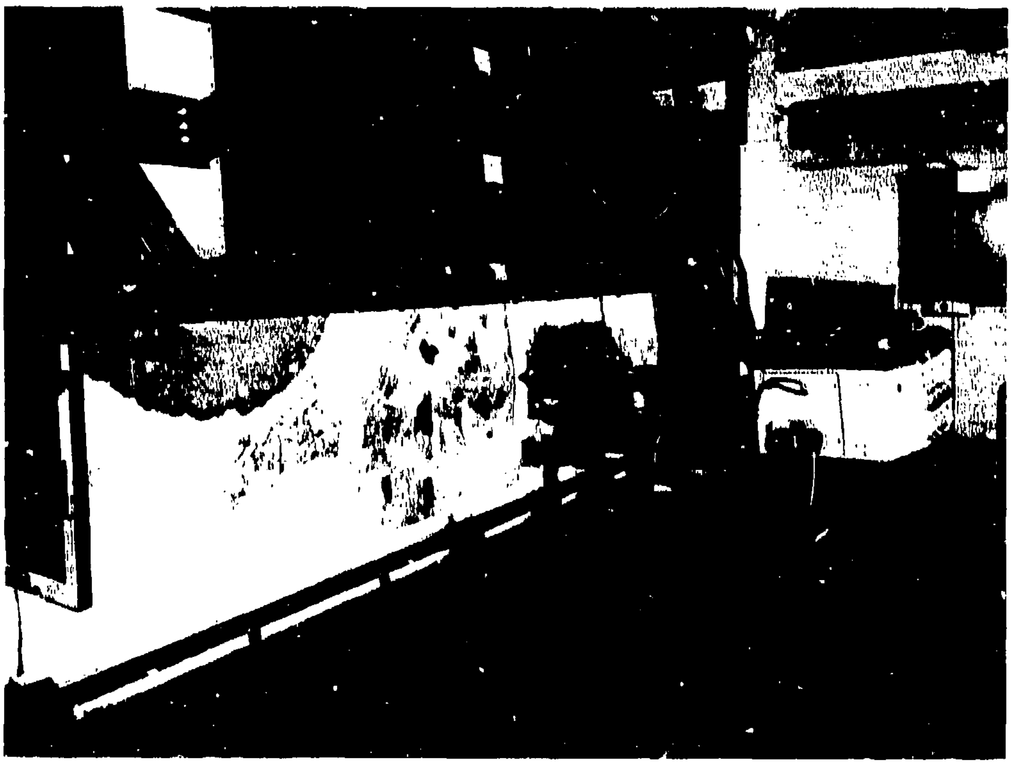


Fig 2 Visual flight system comprising model belt and camera gantry

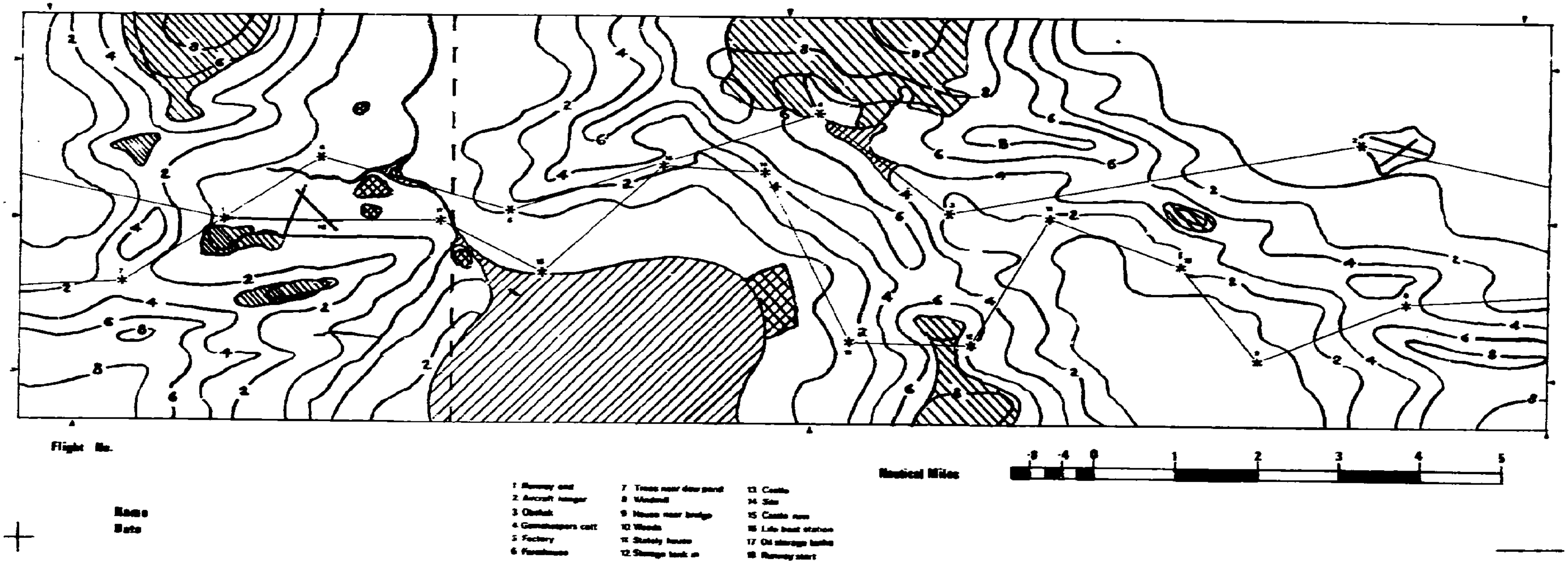


Fig 3 Map of belt terrain showing the waypoints and route for the navigation task

Fig 4 Helmet mounted display viewed from the front to show collimating optics and combiner glass

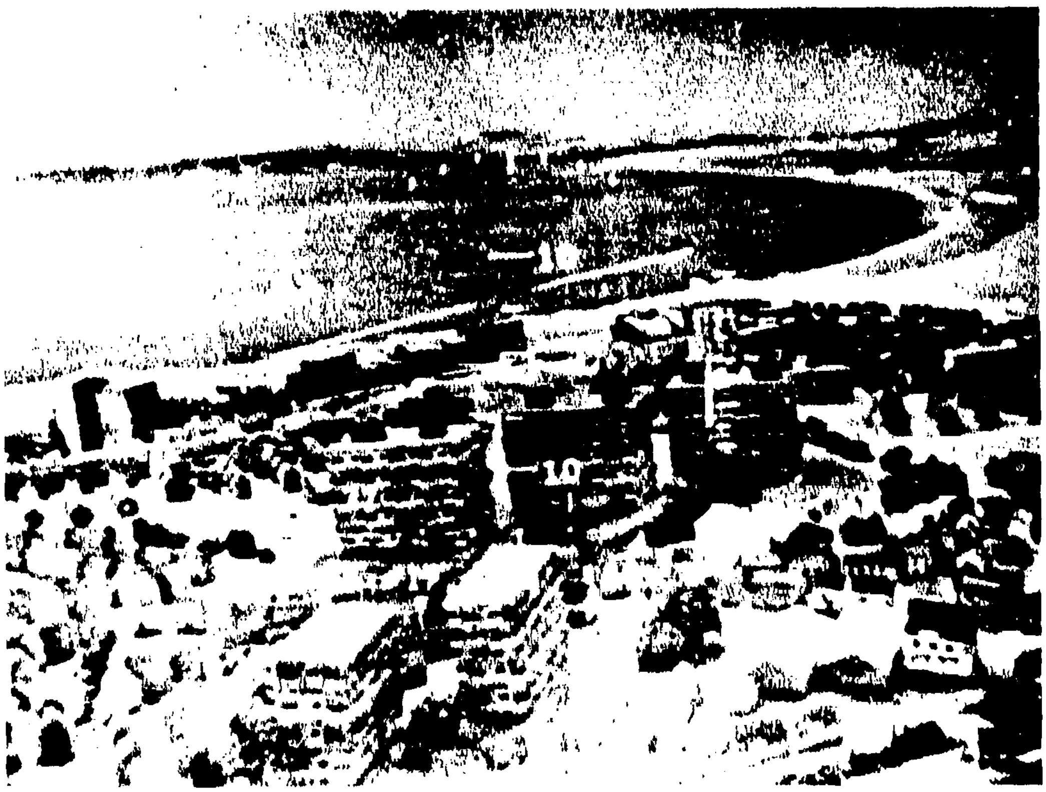


Fig 5 Overlay flight information shown against the outside world picture from the model terrain

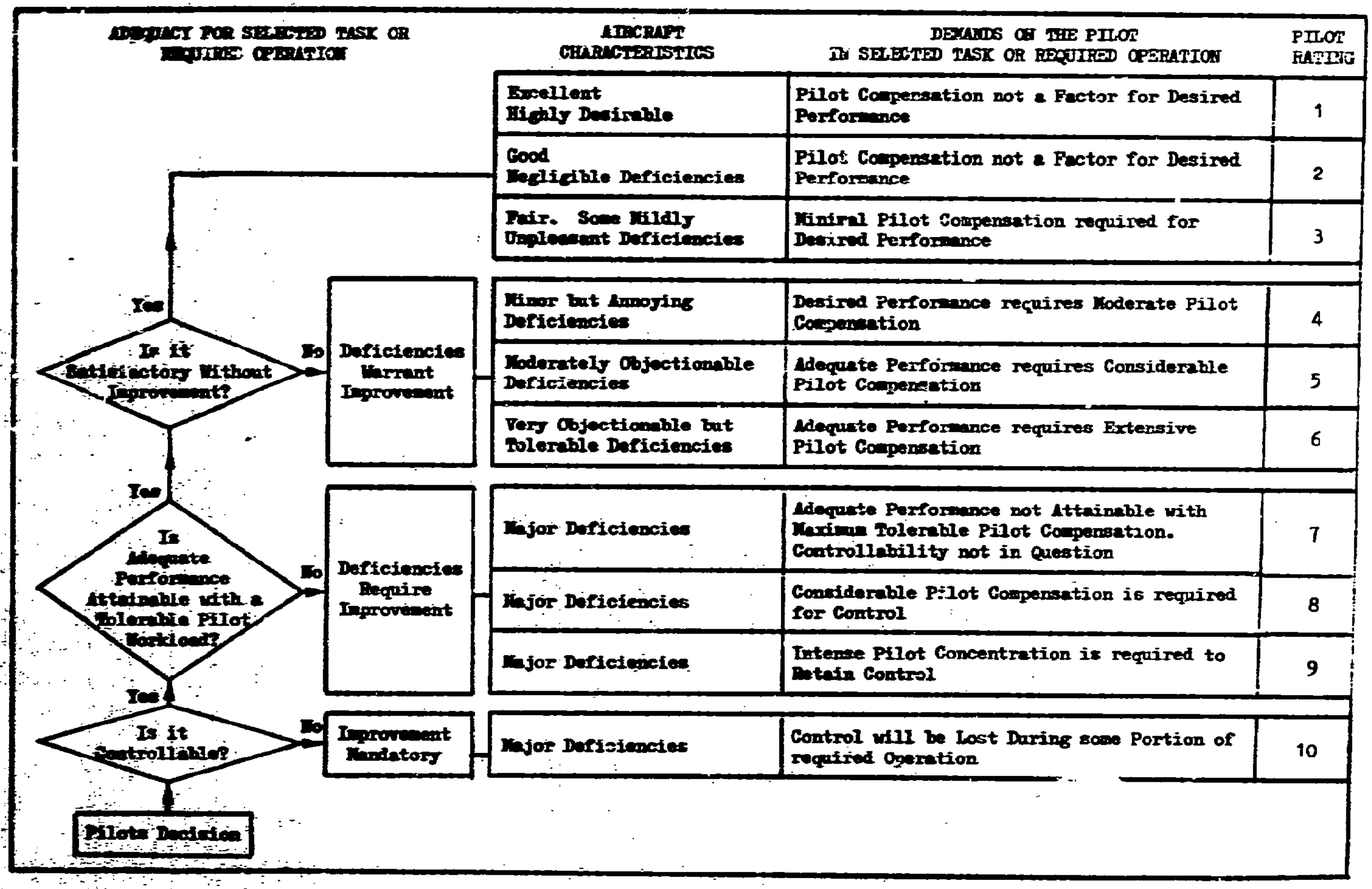


Fig 6 Cooper-Harper rating sheet

Fig 7 Terrain map showing the positions of simulated tanks

USE OF SIMULATION
IN
THE EVALUATION OF THE IFFN PROCESS

J. E. FREEDMAN and S. H. STARR
Systems Evaluation Division
Institute for Defense Analyses
Arlington, Virginia 22202
USA

SUMMARY

An evaluation program has been initiated in the U.S. Department of Defense, Test and Evaluation (DDTE) to assess the ability of the indirect subsystem on the evolving NATO Identification System (NIS) to support the identification requirements of selected air defense weapon systems. It is projected that the evaluation program will consist of two phases: 1) a simulation phase, which will employ a testbed consisting of operational units and manned simulators driven by a central simulation facility; and 2) a limited field test phase, taking advantage of programmed field test exercises to validate the simulation phase, where possible, and enhance program credibility. This paper describes the architecture for the proposed simulation testbed and illustrates its potential utilization in evaluating the performance of a NATO Airborne Early Warning aircraft in support of defensive counterair operations.

INTRODUCTION

It is widely recognized in the tactical community that the inability of key users to discriminate accurately and rapidly between friendly, hostile, and neutral aircraft may significantly limit the effective utilization of air defense weapon systems. This recognition has stimulated activity within NATO to develop an effective NATO Identification System (NIS). This evolving system consists of two complementary subsystems (Figure 1): (1) a Direct Subsystem (DDS), which provides an autonomous identification capability for individual users, the primary element of which is a question-and-answer component; and (2) an Indirect Subsystem (ISS), which formulates identification decisions, procedures, and guidance, and disseminates them to selected users to verify the correctness of their decisions and enhance their confidence in the decision-making process. The ISS is largely embedded in the command and control (C^2) system that is dedicated to air operations.

The U.S. Department of Defense, Test and Evaluation (DDTE), is embarking upon a multiyear program to evaluate the ability of the ISS to support the identification process in an operational environment. A Joint Test Force (JTF) is being assembled to conduct the program with executive direction vested in the U.S. Air Force. This paper describes that program, emphasizing the role that modeling and simulation will play in the evaluation. The next section on *Nature of the Identification Process* places the identification process in perspective, focusing on the relationship of the C^2 system and selected weapon systems in the context of the NATO environment. This provides the basis for the IFFN Evaluation Program, whose objectives and structure are delineated in the next section, *Programmatic Features*. Here are specified the types of tests that are to be employed to accomplish the program objectives. The remainder of the paper is restricted to a discussion of the primary test vehicle: a hybrid, geographically distributed testbed consisting of a central simulation facility, manned operational C^2 systems, and manned mission simulators. The *Testbed Requirements* section summarizes the technical requirements for the testbed and examines the considerations underlying their formulation. This has given rise to a preliminary architecture for the identification testbed which is described under the next heading, *Identification Testbed Architecture*. To illustrate the potential utilization of the testbed, the *Illustrative Test Design* section presents an example of a test design that considers the subphase of the program where a programmed NATO Airborne Early Warning (NAEW) aircraft is employed in support of defensive counterair (DCA) operations. The *Conclusions* portion summarizes the major features of the evaluation program.

NATURE OF THE IDENTIFICATION PROCESS

LIMITATIONS OF THE DIRECT SUBSYSTEM

It is well recognized that a reliable, accurate, and responsive DSS is a necessary component in the evolving NIS. However, it is not in itself sufficient to support all of the requirements for users of identification information. This conclusion follows from the fact that, for densely distributed air defense systems that rely on an autonomous DSS to identify targets independently, the probability is high that an overflying friendly aircraft will be exposed to at least one system that will err in identification. As an illustration, consider the groundbased air defense units (ADUs) deployed in the forward division area (e.g., short-range air defense systems (SHORADS), low-altitude-missile air defense systems (LOMADS)). There would be in excess of a hundred of these systems for a representative division. If these weapon systems were deployed uniformly, even low-altitude aircraft traversing the division area would be exposed to many (e.g., an average of 10 or more) ADUs. Under the highly optimistic assumption that each ADU operator correctly identifies aircraft with probability 0.95, if 10 weapon systems were overflown, at least one of the operators would misidentify the aircraft with probability 0.40 (Figure 2). The fratricidal implication of this misidentification would depend on the prevailing rules of engagement (ROEs), weapon system performance, and target dynamics. It is left to the ISS to ameliorate this fundamental deficiency by disseminating identification information, airspace control procedures, and guidance to these weapon system operators.

C^2 WEAPON SYSTEM RELATIONSHIP IN THE IFFN PROCESS

If an air defense weapon system is to be employed effectively, the operator must detect a target, identify it, and then make an appropriate engagement decision. The C^2 system should play an important role in influencing the ability of the weapon system operator to perform each of these functions (Figure 3).

- *Detection.* The C^2 system can influence the ability of a weapon system operator to detect a target in progressively more detailed ways: (1) promulgation of advanced states of alert (e.g., placing all forces on advanced states of alert to warn of an impending raid); (2) tactical alert (e.g., warning specific weapon systems operators of approaching aircraft); and (3) cueing (e.g., passing relative range and azimuth of a specific target, or set of targets to a weapon systems operator). These inputs, in conjunction with the organic detection capabilities of the weapon system operator, determine the probability that the operator detects a given target and the temporal and spatial conditions under which detection occurs.

- *Identification.* Once the weapon system operator has detected a target, the C^2 system can contribute to the identification process through the following mechanisms: (1) issuance of hostile act criteria (e.g., defining a behavior profile of a hostile intruder that the weapon system operator can use as a basis for evaluating his observations); (2) promulgation of airspace control procedures (e.g., defining a behavior profile of friendly aircraft by establishing a bound on speed and restricting allowable spatial corridors or altitudes); and (3) indirect IFFN information (e.g., passing the C^2 system identification decisions to the weapon system operator). The weapon system operator must synthesize this information with his direct sources of identification data to arrive at an IFFN decision. Once he has reached this decision, the weapon system operator might transmit the result back to the C^2 system as indirect IFFN information.

- *Engagement.* The actions of the weapon system operator are influenced by the result of the identification process, inputs from the C^2 system, and the capabilities (or perceived capabilities) of the weapon. The interaction between the identification decision and guidance afforded by the C^2 system is reflected in the ROEs under which the operator must function.

  As a consequence of this confluence of factors, the weapon system operator may perform one of the following actions (Figure 4):

  - Valid action: (1) Engage and destroy an enemy with probability of kill P_k, depending on weapon capabilities, enemy countermeasures, and the dynamics of the encounter; or (2) not engage a friendly or neutral aircraft.

  - Degraded action: Suffer reduced effectiveness in engaging enemy targets because of time delays (arising from detection, weapon setup time, identification, or coordination with the C^2 system and other weapon system operators) or maldistribution of fire. This action may still contribute to the air defense process if the engagement causes the hostile aircraft to be less effective in performing his mission (i.e., "virtual attrition").

  - Invalid action: (1) Engage a friendly or neutral target and (a) commit fratricide with probability of kill P_k or (b) fail to destroy the target, but degrade confidence in the system and waste ordnance; (2) fail to engage a hostile target, even when engagement is authorized under the prevailing ROEs.

These observations reveal that the IFFN process is imbedded in the broader engagement process and is inextricably linked with the C^2 system. Hence, the IFFN evaluation program will assess the impact of the identification process on the capabilities of a weapon system in the context of the associated C^2 system. Although this is an undertaking of exceptional breadth, it has been extended still one step further: since the identification process is inherently a two-sided process, encompassing attempts of opponents to deceive, exploit, jam, or destroy key elements, the systems and procedures of both projected combatants are included as integral components of the evaluation program.

DISTINCTIVE ASPECTS OF THE CENTRAL EUROPEAN THEATER

The central European theater is of extreme interest to policy planners in the United States and constitutes a bounding case for many of the parameters of interest (e.g., numbers and densities of aircraft and ECM). It is perceived by many that solutions which are proven effective in NATO will prove adequate in less demanding environments.

Accordingly, the IFFN evaluation program is placing emphasis on analyzing the identification process in the context of a projected conventional conflict in central Europe. The major factors in that region that are being considered in the evaluation program are summarized below.

- *Threat Conditions.* In a projected conflict in the NATO Central Region, in excess of a thousand aircraft could be airborne, simultaneously, at altitudes ranging from tens of meters to tens of kilometers. Since much of this air traffic would fly in formations, even radar sensors with an extended view of the battle area (e.g., NAEW aircraft) would probably perceive no more than several hundred radar tracks. The performance of most sensor and avionics equipment will probably be degraded by extensive employment of chaff and jammers carried by standoff and escort aircraft.

- *Ambient Conditions.* The proliferation of many electronic systems that are potentially self-jamming (e.g., Mark X) suggests that electromagnetic interference may significantly degrade the performance of key systems in the NATO Central Region.[1] These problems may be worsened by poor visibility and terrain shielding, which are characteristics of the meteorology and the topography of the region (e.g., low-altitude clouds and fog and intermittent masking of low-altitude targets to ground-based sensors).

- *Nonhomogeneous Allied Aircraft Mix.* There is a broad mix of Allied aircraft types and avionics gear that compounds the problems of both visual and electronic identification.

[1]This is exacerbated by the fact that many of the modes employed by Mark X are incorporated in the Air Traffic Control Radar Beacon System (ATCRBS) which supports civilian air traffic control.

- *C^2 Structure.* The C^2 system associated with air defense in NATO is a unique, complex combination of NATO facilities (e.g., the control and reporting centers of the 412L system in the southern region of the Federal Republic of Germany) and national systems (e.g., the U.S. Air Force's Air Control and Warning (AC&W) component of its Tactical Air Control System (TACS); the U.S. Army's TSQ-73 Missile Minder, for the control of Improved Hawk and Nike-Hercules).

The evaluation program is further complicated by the fact that the identification process is evolving in time as a consequence of programmed and planned changes in several areas:

- Deployment of new weapons with longer range and enhanced lethality (e.g., Patriot, a surface-to-air missile system designed around a phased array radar; the advanced Medium-Range Air-to-Air missile to replace Sparrow).
- New and updated C^2 systems and procedures (e.g., the programmed deployment of the NAEW system, the generation of a modified NATO Central Region Airspace Control Plan).

Accordingly, the evaluation program will establish baselines of performance where that information is perceived to be edifying, and conduct exploratory evaluations of selected programmed and proposed equipment, procedures, and doctrine.

PROGRAMMATIC FEATURES

This section identifies the objectives of the IFFN program and the approach that is to be employed to realize these objectives. It recounts prior relevant simulation activities and the lessons that have been derived from those programs.

OBJECTIVES

The major objective of the IFFN Evaluation Program is to assess the ability of the ISS to support the identification needs of tactical aircraft operators and high-altitude missile air defense system (HIMADS) operators in an operational environment. For the purposes of this paper, the ISS is viewed as the equipment (e.g., sensors, computers, displays, communications) and personnel at key nodes of the C^2 system that supports air defense operations.

The key C^2 systems of interest for the control of tactical aircraft and HIMADS are depicted in Figure 5 for the Fourth Allied Tactical Air Forces (4ATAF) region[1] of NATO in a mid-1980s time frame. The major components of the ISS include:

- *Control and Reporting Centers (CRCs) of the German Air Defense Ground Environment (GEADGE).* These fixed, bunkered systems will constitute the 4ATAF component of the NATO Air Defense Ground Environment (NADGE). The identification officers (IDOs) in these facilities are the focal points of the ISS.

- *Control and Reporting Posts (CRPs) of the U.S. Air Force's 485L System.* These transportable facilities will be able to exchange digital data with GEADGE through the Message Processing Center (MPC). Assistance in the identification process may be forthcoming from its Movements and Identification (M&I) section.

- *NATO Airborne Early Warning (NAEW) Aircraft.* These aircraft will augment the air picture of the ground-based C^2 systems and have the potential to support limited control functions if selected ground-based facilities are inoperative or saturated.

- *Group and Battalion Operations Centers (GOCs and BOCs) Employing the U.S. Army's TSQ-73.* These transportable facilities are equipped with two displays to support the C^2 of HIMADS batteries. The group level is primarily charged with coordinating and managing the air picture while the battalion manages the local air picture and allocates and monitors fire unit performance.

In order for the controllers in these facilities to assist weapon system operators in the identification process, they must be able to perform a sequence of functions: (1) detect and track targets; (2) correlate identification information with these tracks and synthesize it into a correct, timely identification decision; and (3) disseminate these identification decisions to weapon system operators and validate the weapon system's association of that data with the correct targets.

To realize this objective will require the evaluation of two levels of figures of merit. As an intermediate level, data will have to be acquired under operationally realistic conditions to characterize the detection and identification performance for selected controllers and weapon systems operators. This will include:

- *Detection:* Temporal and spatial conditions when detection occurs.

- *Identification:*

  - for those targets that are detected, the percentage that are identified

  - for those targets that are identified, the percentage that are correctly identified

  - the temporal and spatial conditions when identification occurs.

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[1]This region includes the southern sector of the Federal Republic of Germany (FRG).

As an overall figure of merit, it is necessary to relate identification performance to weapon system effectiveness. This will be characterized by computing the likelihood of each event depicted on the tree in Figure 4 for specified environmental conditions.

The initial assessments will establish a quantitative baseline of performance against which proposed improvements to the identification process can be measured. Emphasis will be placed on determining the conditions (e.g., aircraft numbers, ECM levels) where the ability of a controller to perform the subfunctions in the identification process degrades appreciably.

Subsequent assessments will determine the potential improvements in ISS performance that are achievable through several different levels of development.

- *"Black Box" Improvements.* Upgrading or developing new sources of identification information (e.g., developing a new question-and-answer system to replace Mark X/XII).
- *Subsystem Enhancements.* Improving the automated data processing equipment that supports C^2 controllers. One important subissue is the evaluation of the effectiveness of fusion algorithms that have been proposed to facilitate the synthesis of identification information into a decision.
- *System Modifications.* Enhancing the interoperability of tactical data systems (i.e., enabling them to exchange digital track data in real time). Although this capability has been demonstrated, no attempt has been made to quantify its impact on identification performance or weapon system effectiveness. Assessments are also required of the impact of proposed changes to the airspace control procedures in the NATO Central Region.

Since the evaluation program will require either operational units or prototype systems to carry out the assessment, the program will be limited to systems and procedures that could be operationally employed in an early 1980s time frame.

STRUCTURE

In order to realize these objectives, it will be necessary to identify appropriate test vehicles. These potential vehicles fall into two broad classes: simulation and field tests. If the vehicle is to serve the needs of the program, it must be capable of incorporating the distinctive aspects of the identification process that were described in the *Nature of the Identification Process* section. In addition to these attributes of operational fidelity, consideration must be given to such factors as constraints imposed by safety and resource availability, controllability of test conditions, data collection problems, and cost. After these factors were considered, a program was fashioned that focused on the creation of a simulation testbed consisting of operational units, manned simulators, and computer emulations. In view of the complexity of the total system of interest, an essential element of the program was to define a sequence of subphases that progressively considered increased level of C^2 system integration and complexity. This progression is described under the next heading, *Testbed Requirements*.

To enhance the credibility of these simulation results, it is deemed desirable to validate the performance observed in the simulation testbed for limited conditions that can be reproduced using live aircraft and the operational C^2 system. However, since it is not feasible to reproduce realistic operational conditions in peacetime (e.g., limitations on aircraft numbers, trajectories, and ECM), a complete validation of the simulation results cannot be performed using field exercises or a dedicated field test. Instead a limited validation will be sought by demonstrating that the results from the field exercises are reproducible in the testbed. An assessment of ongoing exercise series is currently in process to determine which, if any, field exercise could be employed to support this limited validation process.

RELEVANT SIMULATION EXPERIENCE

The decision to employ a simulation testbed as the primary evaluation tool is based, to a considerable degree, on the experiences of the tactical air control system/tactical air defense system (TACS/TADS) interoperability program. The purpose of that program was to test and certify the technical compatibility and interoperability of U.S. TACS/TADS systems in joint military operations. Participating systems were selected from the four U.S. Services which manifested the following characteristics: (1) mobile, (2) automated or semiautomated, (3) deployed worldwide, and (4) users of selected tactical digital communications links.[1] Some examples of these systems are (1) components of the AC&W subsystems of the U.S. Air Force's TACS, (2) the Army's TSQ-73, (3) the Navy's Naval Tactical Data System (NTDS) and Airborne Tactical Data System (ATDS) and the Marine Corps' Marine Tactical Data System (MTDS).

In order to realize their objectives, a distributed testbed was assembled consisting of the actual participating data systems under the control of a central simulation and monitoring facility. The current mission of the testbed is to support configuration management activities. In October 1980, this configuration management task is to be transferred to the Joint Interoperability for Tactical Command and Control System (JINTACCS) program. JINTACCS is to expand the scope of the TACS/TADS program by testing and certifying the interoperability of tactical data systems that support intelligence, fire support, amphibious operations, operations control, and air operations.

The TACS/TADS testbed established the feasibility of creating a geographically distributed facility consisting of operational C^2 systems linked via leased lines. It also demonstrated the feasibility and flexibility of the centralized control concept, which employs a Central Simulation Facility (CSF) as the focal point of all test activities (i.e., generates all stimuli, coordinates and monitors the testing). This concept is proposed for the IFFN testbed also, although other approaches are still under consideration.

The TACS/TADS testbed, while providing a firm basis for the IFFN evaluation, had a different orientation to its purpose and scope. The IFFN testbed requires significant extensions in the following areas:

[1]Tactical Digital Intelligence Links (TADILS) A and B, which provide roll-call and point-to-point communications, respectively.

- *Participating C^2 Systems:* To assess the ISS of the NIS, it is necessary to incorporate surrogates for selected NATO and Warsaw Pact C^2 systems.

- *Participating Weapon Systems:* Simulated tactical aircraft and SAM weapon systems are to be incorporated to evaluate the interface between the C^2 system controller and the weapon system operator.

- *Evaluation:* The TACS/TADS program was primarily interested in monitoring and ensuring the fidelity of digital data transfer among participating units. The IFFN Evaluation Program is attempting to establish the quantitative benefits that can be derived from the ISS by weapon system operators.

The remainder of this paper describes how these objectives will be accomplished in the IFFN evaluation testbed.

TESTBED REQUIREMENTS

The basis for the simulation testbed is established through the formulation of a set of system requirements compatible with the critical issues to be evaluated. These requirements should define the essential characteristics of the testbed without unduly constraining the design realization. This section of the paper articulates these requirements and examines the considerations underlying their formulation in terms of:

- Scope of the simulation (i.e., geographical arena, facilities represented, the air battle scenario to be played).

- Representation methodology and realism (i.e., fidelity requirements, methods used to represent facilities, sensors, aircraft).

- Provisions for test control and assessment (i.e., scenario preparation, stimulation, monitoring, data processing).

- Realization of the testbed (i.e., modular evolution, flexibility).

SCOPE

The nature of the ISS is such that the testbed must simulate:

- A significant volume of the central Europe airspace.

- Numerous facilities and sensors of various types.

- A large variety of air operations.

The facilities simulated must encompass both the NATO systems and the opposing Warsaw Pact systems. Moreover, these must include not only facilities directly executing air defense operations (see Figure 5), but also any air defense planning facilities[1] and offensive air operations facilities[2] whose actions indirectly impact the identification process. Not counting interceptor aircraft, there are almost 50 individual nodes that must be represented. These compose more than 15 types of C^2 centers and weapons systems. Supporting these systems are an array of over 100 individual sensors of 35 types.[3] However, it is not necessary to cover this entire domain at a uniformly high level of detail. Accordingly, it has been visualized as consisting of two components:

- The *simulation core* - comprising the facilities and airspace of primary interest.

- The *simulation background* - comprising peripheral elements, of interest only because of their effects on the core.

The simulation core is a subregion of limited extent. It constitutes the smallest slice of the systems and airspace necessary to include all primary identification interactions and their consequent operational impact. This slice will be aligned to cover a particular portion of the forward battle area, where (1) intense air activity is expected, (2) the full variety of generic system types are employed; and (3) the full spectrum of identification situations is anticipated. The focal area will be represented to a high level of realism--using live units--and will be extensively instrumented to obtain the required measures of performance.

The simulation background covers a much wider set of facilities and a broader airspace area, encompassing the entire environment surrounding the simulation core. It is required because actions taken within it can affect events in the simulation core.[4] However, it will be represented at a lesser level of realism.

Figure 6 depicts the approximate geography of the airspace corresponding to the above-described components, with the core shown as the black inner region, and the background area depicted as the partially shaded outer area. As depicted, the total area to be covered includes a subset of the Central Region of NATO centered in the FRG forward area. The extension beyond the political borders into Warsaw Pact airspace accommodates early warning systems and allows for the play of the Warsaw Pact systems.

The evaluation issues related to battle intensity and system loadings require that the testbed be capable of supporting a high-intensity air battle scenario. This would correspond to the air activities

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[1]For example, ATAF Airspace Control Center (AACC), Air Defense Operations Center (ADOC).
[2]For example, the Air Tactical Operations Center (ATOC) which supports the tasking of offensive operations.
[3]Some of these are of similar generic type and include existing and new sensors.
[4]For instance, adjacent air defense facilities situated in the background area may provide early warning alerts and cueing to a facility in the core area.

expected during the early phases of a full-scale conventional Warsaw Pact attack. The full variety of Pact and NATO aircraft, encompassing upwards of 35 aircraft types, will need to be modeled. These will be executing the full range of offensive and defensive missions in a high-intensity electronic warfare environment. This scenario also implies that the testbed should have sufficient capacity to provide simulated air traffic comprising up to 500 flights in formations of 2 to 16 aircraft, occurring over a 1-hour time window.

REPRESENTATION OF THE AIR BATTLE ELEMENTS

For the identification testbed to be credible, it must represent each element of the air battle in a sufficiently realistic manner. A variety of simulation methods of varying fidelity are available which might be used. In each case the choice must be made by balancing cost and feasibility against the level of fidelity judged to be necessary.

The term *fidelity* refers to the faithfulness with which the various components of the system are to be represented. The fidelity issue is very important to the credibility and eventual acceptance of the findings of the evaluation program. While achieving high fidelity is a desirable goal, the cost of doing so can be quite high. Costs accelerate rapidly as ever-higher levels of fidelity are approached, particularly in the areas of hardware and software. Moreover, there is a diminishing-returns effect, so that beyond a certain point further improvements to fidelity have a rapidly diminishing influence on experimental results. The goal, then, is to establish testbed fidelity requirements that exhibit a satisfactory balance between cost and fidelity. It is difficult, however, to determine exactly where this balance point lies. To do so would require a series of special experiments designed to compare system responses for emulations having varying fidelity levels. The expense of doing this is justifiable only for certain critical emulated elements, where the cost impact of enhanced fidelity is potentially high. In other less critical cases, where the cost impact is low or the emulated elements are in the background area, the approach will be more judgmental, relying on the prior experience of persons doing the planning and industry estimates. Also, calibration checks on the fidelity will be built into the test design and accomplished early in the test program.

The identification testbed will be a hybrid in that it will employ a combination of methods to represent the full array of systems it encompasses. Figure 7 details the application of the various representations for the NATO forces portion of the testbed. The methods of representation can be classified into two general categories: live participating units and computer models.

The term *live participating unit* (LPU) refers to the mode in which a system is represented by having personnel man either actual operational or surrogate equipment for that system. The testbed will emphasize LPUs as the primary means for representing the air defense systems within the simulation core that are directly involved in identification. The reason for this is that computer models, though economical and easily controlled, become unrealistic for man-in-the-loop systems. In systems of this type, human interactions occur for which relationships between stimuli and response are unknown. This situation exists at a number of critical points in the ISS of the identification process. For example, the IDO in a CRC must interact with his own automated devices and must frequently consult with other persons (e.g., other IDOs, weapons controllers, air traffic controllers) in his own facility and in other facilities. Weapon system operators in turn must synthesize identification data from the DSS in order to reconcile discrepancies with the indirect data furnished by the ISS. Therefore, to satisfy the fidelity requirements, the simulation of these positions must be accomplished with LPUs.

When LPUs are used, the manning of the operator positions becomes an important question. As the number of manned positions rises, so do the difficulties in test control, expense, and risk of confounded results. Consequently, it is important to keep the number of manned positions to the minimum necessary for experimental fidelity. The approach taken will be to have separate positions only for those individuals who either perform or frequently support identification as a major function. Combined positions will be used for those individuals who are not primary players and who do not frequently support identification positions. Steps will be taken to ensure that realistic workloads are placed on the multirole individuals so that the response delays are realistic.

The testbed will employ computer models in cases where well-defined physical processes are to be modeled or where the fidelity requirements for representing the man-machine interaction are less severe. These models fall into two categories: interactive and noninteractive.

- *Interactive models* (in real-time) react dynamically to perceived changes in the air battle situation. They may receive inputs such as data link messages from the other models or LPUs and may initiate messages either on their own or in response to stimuli. The execution of these models is unpredictable and is conditional on the specific dynamics of the air battle. The applications for interactive models will be as follows:

  - Sensor models: these must react to events such as aircraft kills, removal of jammers, and selection of operating modes.

  - Missile endgame models: real-time interactive missile models will be employed to accomplish real-time removal of killed aircraft.

  - Man-in-the-loop system models: these will emulate manned systems where fidelity of representation is judged to have minor impact on the testing results.[1]

  - Dynamically controlled aircraft models: these will represent those aircraft in the scenario whose flight trajectories and actions must be dynamically controlled.

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[1]These constitute facilities that only indirectly support identification--being either neighboring systems located in the simulation background area or higher echelon and peripheral facilities that are infrequently accessed.

- *Noninteractive models* do not react to the air battle dynamics. They are a less complex class of models and simply generate selected messages and actions at preprogrammed times according to a script prepared prior to the test. These models are considered suitable for emulating those facilities that do not dynamically interact with the identification process, but that provide orders, procedures, and other information on a one-way basis. This would apply to certain higher echelon planning facilities. Noninteractive models will also be the means of representing those aircraft following programmed flight profiles.

TEST CONTROL AND ASSESSMENT

The complex and distributed nature of the identification process makes controlled testing a very demanding task. The test conditions will entail executing a highly complex scenario involving operations with many human participants at dispersed locations. Provisions must be made for adequate control and monitoring of the test execution, as well as extraction and processing the necessary data. This includes the ability to

- Prepare and edit scenarios.
- Support the training of test participants in new procedures to be tested.
- Synchronize, coordinate, and distribute the stimulation of all test participants.
- Perform real-time removal of killed aircraft.
- Monitor the status and readiness of all testbed elements.
- Monitor, in near-real-time, key parameters and test events occurring at all participating testbed facilities.
- Extract data from all testbed elements to obtain: (1) as a first priority, data to permit reconstruction of all events affecting each simulated aircraft; (2) as a second priority, diagnostic data for interpreting why actions were taken.
- Coordinate all data extraction and recording activities, occurring locally and remotely.
- Provide sufficient quick-look analysis of test data to determine if a successful test run was achieved.
- Provide adequate data reduction and automatic analysis capability.

TESTBED REALIZATION

The realization of the testbed must conform to the strategy planned for the progressive evolution of the evaluation program and the modifications and expansions anticipated over its lifetime.

As noted in the *Programmatic Features* section, the evaluation program is structured to examine progressively increasing levels of system complexity ranging from a fully autonomous and decentralized operational mode to the fully intact centralized air defense system. This progression is based on the principle that it is easier to go from a simple to a complex testbed as each testing stage benefits from the experience gained in the prior stages. This testing strategy implies a progressive expansion of the testbed occurring in six steps as follows:

I. Autonomous SAM battery
II. Autonomous SAM battalion
III. Group control of SAMs
IV. Generic USA-USAF ground-based C^2 system
V. NAEW augmentation of ground systems
   a. Augmentory sensors mode
   b. Backup CRC mode
VI. Full NATO C^2 system

The required phasing of the testbed buildup, in terms of the C^2 facilities and air defense weapons to be represented, is shown in Figure 8. The development and implementation cycle must be geared to this progression, meeting increasingly demanding requirements at each step. The testbed should be designed to facilitate the required series of modular expansions to the final full system configuration.

There are several reasons why flexibility is required in the identification testbed:

- *Imprecise definition of the air defense system.* The IFFN Evaluation Program will focus on the mid-1980s time period, assessing the identification capability that might evolve by that time if current trends in C^3 system and identification sensor-development and deployment continue according to projections. Some of these systems will be only vaguely defined at the time of the earlier stages of the testbed development. Therefore, frequent revisions can be expected.
- *Necessity for incorporating proposed system improvements.* There must be sufficient flexibility to allow the new software algorithms, sensors, display concepts, etc., to be incorporated. This will include items such as Mark XII improvements, new identification sensors, automatic data links, and new switch actions and display formats. Other enhancements such as trial algorithms for fusion of local identification data sources and correlation of ISS data will need to be integrated into the operational software of the various tactical data and weapon systems participating in the testbed.
- *Accommodation of testing variants.* The testbed must be able to easily change the various environmental factors and must be reconfigurable to represent various disruptions to the C^3 system expected under combat conditions.

- *Unanticipated modifications.* As the testing progresses and experience is gained, improvements to the testbed will be desired. The testbed should be capable of being easily modified to implement these improvements.

The need for flexibility as detailed above, dictates the use of a high-level computer language and a general-purpose computer operating system. In addition, provisions should be made for inclusion of adequate software development aids and future hardware expansion.

IDENTIFICATION TESTBED ARCHITECTURE

Several alternative architectures are potentially capable of satisfying the requirements identified in the preceding section and are under active consideration. These embody varying degrees of centralized testbed management. The final selection of an architecture is the prerogative of the JTF and will be based on the findings of cost and feasibility studies now underway. This section briefly reviews the essential features of the one option that tentatively appears to be the most well-suited--a centrally-controlled distributed testbed concept patterned after the approach used in the TACS/TADS testbed.

OVERVIEW OF THE CENTRALLY-CONTROLLED DISTRIBUTED CONCEPT

This section provides a brief overview of the essential features of the centrally-controlled distributed concept and its underlying rationale.

The centralized concept employs an array of geographically distributed test facilities with a central simulation facility (CSF) providing strong centralized control. This CSF directs and monitors all testing operations and is the source of all stimulation for the entire testbed. This concept represents a middle ground between a fully unified testbed having all facilities and resources concentrated at one installation,[1] and a fully decentralized testbed composed of locally controlled, widely dispersed facilities coordinated by voice.[2]

The tradeoffs among these various architectures are the extra development cost, time required, and risk of creating special centralized facilities versus the savings they produce in facilitating the actual test operations. The final decision will be based on the total cost, risk, and time required for the entire program, which is the sum of both the development and test operations phases. The centralized control concept offers effective control of test operations at reasonable development cost[3] and therefore appears particularly well suited to the above criteria.

To ensure that the simulated inputs driving the various participating systems will be standardized and controllable, the functions associated with simulation and control will be physically and logically segregated from the live systems being evaluated. A common simulation system, specifically developed for the identification evaluation, will be employed. Under this approach, the built-in simulation features currently available in some of the systems under study will not be used. This is to avoid problems that could develop from using a variety of simulators, each developed to satisfy different and often unknown criteria.

The testbed facilities will be divided into two functional entities: (1) the various live participating units (LPUs) representing the main NATO and Warsaw Pact tactical data and weapon systems operating in the simulation's core region; and (2) a simulation control system used to stimulate, control, and monitor the testbed, and also to emulate systems in the simulation's background region.

The general architecture for the centralized control testbed concept is shown in Figure 9. With this concept, the simulation control system will consist of three components: (1) a CSF that will support and control all testbed operations; (2) a series of satellite simulation units (SSUs), one servicing each LPU site; and (3) a data processing support facility.

The SSUs will act as interface buffers between the LPUs and the simulation control system. To minimize cost and programmatic risk, the live units required for the testbed will be assembled from existing facilities. Modifications to these facilities will be minimized by tailoring each SSU to the peculiarities of the LPU it services. Since most facilities that are to be used for the LPUs are not available full time or are difficult to relocate, they will remain in place and will be connected to the testbed via telephone lines. The identification testbed will therefore be geographically distributed.

Use of a distributed architecture makes communications an important factor. As indicated in Figure 9, there will be two networks, each including both voice and data channels: (1) a test control network over which all monitoring, control, and stimulation information will be passed; and (2) an operational network comprising the operational circuits that normally interconnect the various air defense system nodes. The CSF will be the hub through which all communications are routed (Figure 9). This routing allows (1) all operational message traffic to be monitored and recorded at the CSF, (2) rapid reconfiguration to any of the C^2 configurations required, and (3) control and stimulation to be centralized and conducted from the CSF via the test control network.

SIMULATION CONTROL SYSTEM

This section provides additional details on the attributes of the simulation control system.

The simulation control system will support the following testbed activities:

- Software checkout and modification

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[1]The Federal Aviation Administration's air traffic control simulation facility at the National Aviation Facilities Experimental Center in Atlantic City, N.J., is one example of this approach.
[2]The NATO Programming Center's NADGE simulation exercise concept is an example of this approach.
[3]The development cost is estimated to be considerably less than the manpower costs for the test operations.

- Test preparation
- Test operations
- Post-test evaluation

The processing tasks associated with these functions will be divided among the CSF, the SSUs, and a data processing support facility. The general approach will be to strive for a high degree of centralization of all testbed functions at the CSF. The degree to which full centralization is achieved in practice will be governed by tradeoffs between factors such as cost, technical risk, and schedule constraints.

To keep CSF costs at an acceptable level, those tasks that demand large computer resources but can be done offline on a low-priority, non-real-time basis, will be considered for implementation at the support data processing facility. This support facility will be a batch processing computer center located in the vicinity of the CSF site. As another example, functions that might create excessive communications loads if implemented at the CSF may be offloaded onto the SSU minicomputers (e.g., recording of large amounts of extracted data, modeling of sensors feeding a particular LPU).

As the build-up of the testbed progresses, the CSF will include the software and interactive programming aids to support development and debugging of software modifications and modular expansion of the system to new levels of capability. To facilitate this process, the CSF will be developed using commercial minicomputer components. All applications programs will be written in a high-level language (e.g., FORTRAN). A commercially available computer with a real-time disk operating system having interactive editing, file management, compilers, loaders, and debug aid features, will be used.[1] The CSF hardware will include CRT display terminals, medium/high-speed printers, disk memory, and tape drives.

The simulation control system will include a package that provides the capability to generate and modify testing scenario tapes. A scenario tape will consist of aircraft flight events, scripted avionics actions, and other programmed events. An interactive keyboard and a graphics display terminal will be included to permit an operator to modify quickly an existing scenario using fast-forward or reverse scanning. A threat library of attack profiles and aircraft operating characteristics will be included in the data base.[2] With this library, the operator can efficiently assemble any desired air battle using only a qualitative description of the scenario entered.

The relationships between functional elements associated with the test operations are shown in Figure 10. The CSF will originate all testbed stimulation, ensuring that proper coordination and timing are maintained throughout the entire testbed. The basic stimulants will be preprogrammed air traffic and scripted events read from the scenario tape. The capability to supplement this as necessary with overlaid dynamic inputs--entered by operators using the set of interactive display terminals shown in Figure 10--will be available. These operators can play the role of pilots, controlling the actions and flight paths of simulated aircraft.

A family of interactive software models will represent the sensors. These will act on the merged programmed/dynamic air truth for the aircraft flying within their coverage envelope, determining the sensor response to the input stimuli, injecting measurement errors consistent with the electronic environment, and synthesizing a sensor data report for each detected true or false target. To minimize communications costs, sensor models will reside at the live or emulated facility they are feeding. Thus, some models will reside in SSUs while others will reside in the CSF. Also, in cases where raw video signals are required to drive radar processors in the live units, video generators will be incorporated into the SSU to provide the required analog signals for the LPU. These generators will be driven by the software models.

To save communications costs, air truth data will be distributed to a LPU only when the aircraft is within coverage of that unit's sensors. This condition will be determined in the CSF computer using prestored coverage maps, incorporating both local terrain masking and radio horizon effects. Moreover, only events (e.g., the occurrence of a maneuver) will be distributed, thereby avoiding the necessity for high-rate, periodic transmissions of absolute position updates. The actual positional computations will be performed at the SSUs using analytical flight models installed in the SSU processors. These will integrate event data, using a prestored aircraft flight characteristics data base, to predict the exact position of the aircraft at the time of the next sensor observation. These outputs will activate a set of sensor models residing in the SSU which represent the LPU sensor array.

The package of models designed to represent those facilities in the testbed that are not being played live will reside in the CSF. All the positional computations and sensor modeling for these emulated facilities will also be performed there.

In the cases where emulated facilities are required to have a communications interface with a live facility, the following provisions will be made. If only a data interface is required, it will be accomplished via an actual operational data link. Where a voice interface is also required, the concept of operations depicted in Figure 11 will be followed. With this concept, a multirole operator from the testing staff will act as the speaker. He will control the operation of a number of models, listening and responding to the voice contacts and initiating voice transmissions on cue from the models. A display terminal will provide prompts and other data as necessary to assist him in performing the above functions.

Real-time removal of killed aircraft will be accomplished using missile endgame models residing in the CSF, which will be executed whenever an "engage" action occurs at any of the represented weapons. If the aircraft is indicated as *killed*, further dissemination of its air truth will be inhibited.

The CSF will include circuit switching, buffering, and format translation equipment to permit it to act as a central switch point for the operational communications network. This will allow dynamic reconfiguration to any of the C^2 modes of interest to be accomplished quickly. The communications processing package

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[1]Digital Equipment Corporation's RSX11-D operating system is an example of the capabilities required.
[2]The NATO Programming Center's threat library is one possible source for this data base.

will allow all operational and test control data messages to be monitored and recorded on tape or disk.

The CSF will serve as the central command post for the testbed and will include a number of control consoles and voice communications outlets dedicated to this purpose. This equipment will display the status information, provide the switch actions, and provide the communications for the test director to assess the testing situation and take appropriate actions.

Data extraction is another important function performed in the test operations mission. To meet the requirements delineated in the *Testbed Requirements* section, the data recording design goal will be to provide, at a minimum, the data necessary to permit time-ordered reconstruction of the system's perception of any aircraft in the scenario and all actions taken affecting that aircraft. In addition, as much diagnostic data as is reasonably possible will be recorded. The recording of diagnostic data will be selectable depending upon the loading conditions in the test. To minimize the multiplicity of data tapes, the data recording will be centralized as much as possible depending on the data communication costs affordable for this function. It is expected that all data items flowing through the CSF will be recorded there. This will be supplemented by selectable portions of the participating unit data bases, transmitted to the CSF for monitoring and recording. In addition, the organic recording facilities of the LPUs themselves, augmented where required by SSU recording capability, will be used to record the local data base to the highest feasible level of detail and sampling rate.

Post-test data processing will consist of two types of capabilities: quick-look evaluation and extended analysis. The quick-look evaluation will be performed in near-real-time using the data processing hardware capabilities of the CSF. To meet this need, the CSF will be able to provide aggregated summaries and filtered playbacks of the data extracted from its own internal data base. These will allow indication of a successful test and preliminary assessment of results.

The extended analysis capability will employ more extensive resources offered by the support data processing facility. An existing facility that features extensive peripherals, interactive terminals, and graphics capability will be chosen for this purpose. It will merge the multiple extractor tapes from the various LPU sites with the CSF tape to produce a master merged data set. This master data set will then be chronologically ordered and sorted into a set of distinct files, each describing the timeline of all events for an aircraft played in the scenario. A library of automatic data analysis programs will be developed to process these files and extract the measures of performance requiredto resolve the critical issues. In addition, an extensive set of interactive diagnostic analysis aids will be made available. These will enable a data analyst to filter the data base by time, by air target number, by target classification, and by facility. Data can be selected for either tabular or graphic display. The amount of hard copy will be minimized and will be provided only for specific records requested by the analyst.

Figure 12 shows the layout envisioned for the CSF. It comprises four areas: a testbed command center where observation, control, and monitoring would occur; a computer room containing the data processing hardware and peripherals; a software development area containing a number of CRT terminals; and an interactive emulation area where the simulated pilots and the multirole operators of the emulated facilities models would be located. Figure 13 is an artist's rendition of the testbed command center showing the large screen display, status boards, test control consoles, and an observation gallery. The size and component elements of a typical SSU are indicated in Figure 14.

Due to its unique requirements, the CSF is the only portion of the testbed that cannot be provided by an existing facility. However, there are available a number of off-the-shelf simulation systems, of more limited capability, that could provide a starting point for creating the CSF. This would reduce the cost and risk as compared to starting afresh. These systems are being reviewed to determine which of them offers the best initial point for a buildup to the CSF requirements--at a minimal cost and in the shortest time.

The location of the site selected for the CSF in relation to the LPUs is highly important to the management and successful execution of the test program. A number of factors must be weighed in this selection:

- Communications costs
- Travel time between CSF and LPUs
- Proximity of an adequate support data processing facility
- Availability of necessary facilities (e.g., billets for JTF staff)
- Security provisions
- Availability of support personnel.

A study is being conducted that will consider these factors and recommend a site.

LIVE PARTICIPATING UNITS

The LPUs constitute those air defense systems that will be "live players" in the testbed. Under the centrally-controlled distributed testbed concept, these units will be assembled from existing systems in the United States and connected to the testbed. Where possible, the LPUs will be actual production units. As a second choice, a trainer or an engineering simulator for representing the system will be used. When neither of these are feasible, a general-purpose simulation facility will be modified and used as a surrogate.

A survey of all known U. S. air defense facilities was conducted to identify and characterize those that could potentially fulfill the needs of the testbed. Figure 15 summarizes the survey results, showing the location, type, and application of facilities being considered as potential LPUs.

The final selection of facilities has not been made at this time. It will be driven by considerations

such as availability, interface requirements, location, and supporting facilities. The need for brevity precludes a review in this paper of the tradeoffs governing particular facility selections for all the LPUs. However, to illustrate how the various types of facilities (i.e., production unit, trainer, general-purpose simulator) will be employed, three are discussed: the Battalion Operations Center (BOC), the NATO Airborne Early Warning (NAEW) aircraft, and the Warsaw Pact (WP) C^2 surrogate.

A number of BOC (TSQ-73) production units are based in CONUS. The system at Fort Bliss, Texas, is currently an active participant in the TACS/TADS testbed. Therefore, an interface to another similar remote simulation center should be relatively easy to accomplish. An operational BOC can be readily interfaced with the simulation control system by switching off its live radar and feeding simulated radar video signals, generated by the SSU, to the radar input channel. Software modifications to test new automated identification aids and to provide additional data extraction and recording would be required. However, these can be incorporated into a special version of the operational program that would be loaded prior to the start of a test. A further consideration is that the system is owned by the U.S. Army, which has a high interest in the success of the evaluation. These considerations suggest that the use of an operational TSQ-73 as the BOC participating unit is an attractive option.

A number of operational E-3A aircraft, the U.S. forerunner of the NAEW, are based in CONUS. However, these systems are heavily utilized and, in contrast with the BOC, are unlikely to be committed to the testbed as this would constitute an inefficient use of a large aircraft. Fortunately there are a number of E-3A simulators that are potentially available: two used for crew training and several others for development purposes. Interface with the testbed would occur through a digital interface, with the SSU supplying digital radar reports to the NAEW processor. The simulator would copy the TACS/TADS testbed interfaces with the E-3A, currently under development. As in the case of the BOC, a special operational program version will be developed for use during the testing. These considerations point to the use of one of the E-3A simulators as the most viable choice for the NAEW participating unit.

The WP simulator LPU will represent key Pact frontal air defense C^2 elements defending a slice of the Pact territorial airspace in the NATO Central Region. It will include only those elements that could potentially influence the NATO identification system, for both defensive and offensive operations. A number of facilities would be involved in this role, but these could be represented using a single simulator that was appropriately partitioned. Since the evaluation focus is on how the NATO operations are influenced by the actions of the Warsaw Pact, the fidelity requirements for the WP simulator LPU are considerably less severe. Thus, little disadvantage would result from employing a more aggregated C^2 representation of this system. Consequently, a generic C^2 simulator facility would appear to be the best choice for representing the WP C^2 system.

ILLUSTRATIVE TEST DESIGN

In a simulation testing program, the effort directed to the formation of the testbed must be supplemented by adequate planning for meaningful experiments with the resource being created. This portion of the paper addresses the important question of experimental design and provides an example of how this is being incorporated into the planning of the overall evaluation program. The example presented pertains to the portion of the test program that examines identification when an NAEW, acting as a backup CRC, is supporting defensive counterair (DCA) operations. This example was selected because of the particular interest of the conference in applications to airborne systems. These experiments are planned for Stage V of the testing program, at which point the NAEW simulator and the airborne interceptor simulator will have been incorporated into the testbed. The segment of the air defense system that will be represented and the testbed facilities involved are indicated by the shadod elements of Figure 8.

GENERAL PROCEDURE

The general procedure being used to develop the experimental designs can be summarized as follows:

- Obtain familiarization with the concept of operations for the facilities involved.
- Specify the identification issues that are to be examined and the criteria by which they will be assessed.
- Identify all direct and confounding variable factors and their possible variants.
- Design a matrix of experimental conditions to be tested.
- Derive a testing schedule based on the experimental design.

NAEW-DCA CONCEPT OF OPERATIONS

In a typical air-to-air encounter involving a DCA interceptor under NAEW control, the following events could occur. The NAEW aircraft would be positioned in an orbit and would provide early warning of intruding aircraft, at a range determined by the orbital altitude and position, the ECM conditions, and the size and altitude of the aircraft. These aircraft may be hostile, or they could be homeward-bound friendly aircraft returning from offensive air support missions. The actual configuration of the NAEW crew has not yet been specified. However, if it is compelled to function as a backup CRC, it is postulated that the NAEW crew will include a surveillance operator who will initiate and maintain tracking of detected aircraft, an identification officer (IDO) who will assign an identity, and a weapons controller who will direct a fighter to the vicinity of the threat. The IDO will utilize both direct identification aids and any indirect information available to him to arrive at an identity decision. For simplification, the scope of this testing phase will limit the indirect information to nonreal-time alerting of the presence of enemies or friends in the general area. The NAEW aircraft's direct aids will consist of selected organic active and passive identification devices, flight plan data, and knowledge of airspace control procedures. The NAEW aircraft may also have automatic decision-making aids imbedded in the operational computer program that perform the fusion of all indirect and direct sources of identification data into an identification decision. Using these "black box"

and system aids, the IDO will attempt to provide timely discrimination between friendly, hostile, and neutral aircraft.

If the assignment is other than friend, depending on the tactical situation, the weapons controller may dispatch interceptors to attempt to ascertain or confirm identity, and if necessary to counter the threat under one of three modes of control: broadcast, loose, or close control. In broadcast control, autonomously operating interceptors patrolling the area are alerted to the presence of hostiles or unknowns by means of broadcasted position information--no interceptor vectoring is performed. In the other two modes, the controller pairs available interceptor resources to the threat. In loose control, the interceptors are given range and bearing to the general vicinity of the threat; the individual pilot assumes autonomous responsibility for the intercept and tactics in accordance with the rules of engagement (ROEs). In close control, the controller continually vectors the aircraft until contact with the threat is made.

It is beyond-visual-range (BVR) engagement that is of most interest to the identification program. In BVR conditions, when the interceptor pilot finally assumes control, he must acquire and lock onto the target, identify it using his direct onboard identification aids and any indirect identity information available, position his aircraft within the firing envelope, fire and guide the weapon, and then execute an escape maneuver. The outcome will depend on the missile flyout, target vulnerability, and countermeasure actions taken by the target.

When a pair or more of interceptors are encountering multiple targets, the initial period of the engagement is crucial to the outcome. During this period, in addition to the usual piloting tasks, the pilot must (1) perform coordination with his wingman, (2) interpret his own onboard radar and identification aids data, and (3) correlate his own data with indirect data provided from the NAEW aircraft. This constitutes an extremely heavy workload for the pilot.

ISSUES TO BE EXPLORED AND CRITERIA FOR ASSESSMENT

The Air Force Avionics Laboratory is embarking on a simulation program to evalute the identification performance of autonomous airborne interceptors and the impact of improved identification performance on interceptor effectiveness. The IFFN Evaluation Program will not duplicate these analyses but will extend them in the following directions. To assess the utility of the ISS, a baseline will be established to determine *the level of interceptor effectiveness when it is subject to alternative levels of NAEW control (e.g., close, loose, or broadcast control).*

In particular, an assessment will be made of *the extent to which the identification capability associated with the NAEW-DCA system restricts airborne interceptor effectiveness.* To establish a bound on this issue, performance can be evaluated for two cases: (1) identification is assumed known for a target, coincident with detection (i.e., "perfect" identification performance); and (2) the NAEW-DCA system must identify aircraft using available sources of information.

These results will provide a baseline of system performance and suggest the potential improvements that can be obtained by enhancing identification performance. If it is demonstrated that enhanced identification performance can significantly improve interceptor effectiveness, a sequence of exploratory experiments should be conducted to assess proposed techniques for upgrading the identification function. This raises the following subissues.

- To what extent can identification performance and interceptor effectiveness be enhanced by:
  - "Black-box" enhancement (e.g., an enhanced Mark XII; deployment of an Electronic Support Measure (ESM) System on the NAEW aircraft).
  - Subsystem improvements (e.g., sensor synthesis algorithms for the airborne interceptor and NAEW aircraft).
  - System modifications (e.g., use of a digital data link, with relative navigation properties, to support the exchange of information between the airborne interceptor and the NAEW aircraft).

As noted in the *Programmatic Features* section, these issues will be assessed by evaluating two levels of figures of merit. At an intermediate level, data will be collected to characterize the sequence of steps leading to a controlled engagement. Emphasis will be placed on characterizing the detection and identification process by the participants (e.g., temporal and spatial conditions when the function is performed). As an overall figure of merit, the likelihood of alternative engagement outcomes will be computed (Figure 4) for specified environmental conditions.

VARIABLES

The exploratory evaluations cited in the prior section give rise to a significant number of independent experimental variables. For the two participating systems, these include variations in (1) the black boxes composing their direct subsystems to support identification, (2) personnel experience, (3) identification fusion algorithms, (4) level of control (ranging from close control to procedural control), and (5) level of communications between the two systems (ranging from unsecure voice to a secure, ECM-resistant, digital data link with a relative navigation capability). A conservative estimate of the number of test configurations of interest exceeds five thousand.

Each of these test configurations may require evaluation over a broad spectrum of environmental factors. A representative set of these environmental factors is summarized in Table 1. It can be seen that if all possible combinations of system configurations and environmental parameters were to be assessed, it could mandate enormous numbers of experimental runs.

EXPERIMENTAL DESIGN AND SCHEDULE IMPACT

Since the number of possible test conditions of interest is so large, it is obvious that a full factorial design (i.e., one that tests all possible conditions) is unrealizable. Therefore, it is important to find a way to select a relatively small subset of test conditions that can be run within the time constraints on the testing, but that will still provide valid conclusions on the issues. To achieve this, a combination of enlightened judgment and efficient experimental design techniques must be used to isolate and examine only the most critical factors.

Prior to the onset of testing, filtering techniques including analytical studies, fast-time computer simulations, and expert judgment should restrict the factors for initial consideration to a reasonable number (between 15 and 30). Then efficient experimental design techniques, especially those making use of sequences of fractional factorial experiments[1], could probably be used to systematically identify and study those factors having largest effects. With such designs, a relatively large number of factors can be examined using a relatively small number of test conditions. However, there is a penalty associated with using an experimental design that is made up of only a portion of the full set of experimental conditions. Since not all conditions are run, not all effects (both main effects and interactions) can be evaluated. For a given experimental design size (i.e., number of experimental conditions to be run) only a certain number of effects can be examined, so the tradeoff is between the number of main effects which can be estimated (the number of factors which can be considered) and the number and order of interactions which can be estimated (the number and complexity of relationships between factors which can be considered). Thus, when many factors are examined using fractional factorial designs with a small number of runs, unless many effects are truly negligible, results are likely to be misleading. A way to avoid this difficulty is to have the number of runs be adaptive to the number of significant effects discovered.

An example of one adaptive testing approach under consideration is the usage of fractional factorial designs in a multi-stage adaptive testing cycle. In this cycle the first stage is a wide-coverage screening experiment where a relatively large number, N, of factors (say, N between 15 and 30) are examined with a relatively small number of runs (possibly as small as N + 1). The hope is that many effects considered will actually prove to be negligible so that common sense can be used to interpret initial results and enable selection of relatively few factors and effects for further study. If too many effects are large, additional runs will be necessary to make sense out of the results. The number of additional runs required could vary from a few (2 to 4) to a larger number (say, 256 if N = 15) if there is reason to suspect that all main effects and two-factor interactions are large. Typically, however, a total of 2N to 3N runs will be required to become reasonably comfortable that the most important effects have been identified.

Further stages of the adaptive testing cycle could proceed in two directions. First, factors identified as critical in the screening experiment could be studied further, especially by investigating optimal and break-down conditions for quantitative factors. Second, new factors could be added as the testbed expands. Systematic use of fractional factorials and other formal experimental design techniques could be especially useful when adding factors since each new series of runs contributes not only to understanding of the new factor but also to increased understanding of all other factors under consideration. That is, formal experimental design provides a framework for analyzing test data not simply within a particular testbed configuration but within a total data base where each run complements every other. Furthermore, since many of the measures of effectiveness under consideration are essentially averages of many observations taken during a run, the probabilistic assumptions (especially independence and normality) necessary to make statistical inferences using analysis of variance are likely to be satisfied for much of the test data. Thus, very standard statistical techniques are likely to permit justifiable confidence statements about test results.

It is estimated that the above-described testing program applied to the NAEW-DCA phase of the identification evaluation would require about four to six months to complete for a full scientific exploration of all factors. This time could be reduced if the number of factors were arbitrarily restricted.

CONCLUSIONS

The air defense systems that would be employed in a large-scale intense conflict have grown so complex and extensive that it is no longer feasible to evaluate them fully using live field tests. The tremendous expense involved, the numerous peacetime restrictions on airspace and electronic emissions have constrained the practice of large-scale field testing to the point where simulation now offers greater potential for realism. Even so, using simulation as an evaluation tool has dangers, and its potential will not be realized unless:

(1) The simulation concept employed is adequate for examining the critical issues which need to be studied.

(2) An adequate experimental design is prepared and followed.

(3) Steps are taken to make the simulation findings credible to the user community.

This paper has described how these standards are being applied in the case of the evaluation of the identification process. It has reviewed the comprehensive approach being taken to define the testbed, and described a proposed distributed testbed with centralized control. This concept offers high flexibility, controllability, makes maximum use of existing resources, and has the potential to offer the lowest overall program cost.

Experimental design is another major consideration in this evaluation where there are a large number of factors influencing the effects and consequently an enormous number of possible test conditions. Since it is unfeasible to test every condition, experimental design techniques such as fractional factorial design must be employed to economically screen out the less important factors. As an illustration of how these

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[1]A full treatment of this and other design techniques can be found in "Experiments: Design and Analysis," J. A. John and M. H. Quenouille, Macmillan, 1977.

tools can be used, the paper described the experimental design efforts for a portion of the evaluation program of particular interest to this conference (i.e., the NAEW used in the backup CRC mode in the DCA mission).

Although, simulation has the potential for fewer artificialities, it suffers from a credibility gap relative to results from field tests. This gap can be narrowed, but never completely eliminated, as the reason for using simulation paradoxically precludes any complete validation (because we cannot afford to create the same conditions in real life). The IFFN program plans to attack this problem by performing calibration checks against data from limited field exercises in the hope that, by demonstrating that the testbed can duplicate these results, confidence in it will be established.

The IFFN Evaluation Program is still in its early stages of definition with testing scheduled to begin by mid 1981 and extend over a period of two to three years. Therefore the description of the program presented in this paper should be considered as tentative and subject to revision.

Table 1. ENVIRONMENTAL FACTORS

Aircraft Attributes (for friendly, hostile, and neutral aircraft)
• Numbers • Densities • Missions - Apportionment[a] - Aircraft type, model - Ordnance (e.g., air-to-air missile characteristics) - Avionics gear (e.g., transponder type) - Flight profile[b] (e.g., origin, objective, dynamics)
Electromagnetic Attributes
• Electromagnetic Interference (e.g., Mark X mutual interference) • Electronic countermeasures - Active --victim (e.g., interceptor radar) --type (e.g., noise jamming) --power --jammer platform (e.g., standoff jamming) - Passive --type (e.g., chaff) --platform
[a]Percentage of aircraft assigned to alternative missions (e.g., defensive counter air, close air support/battlefield interdiction, offensive counterair) [b]This will be constrained by postulated visibility conditions and terrain features.

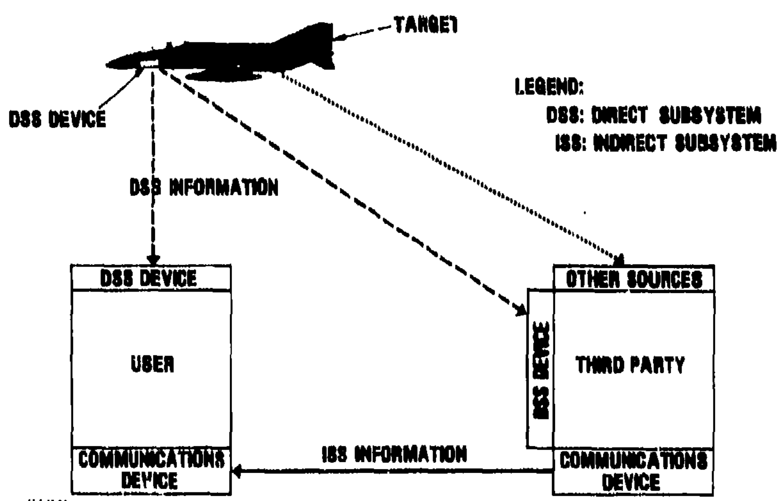


Figure 1. NATO IDENTIFICATION SYSTEM CONCEPT

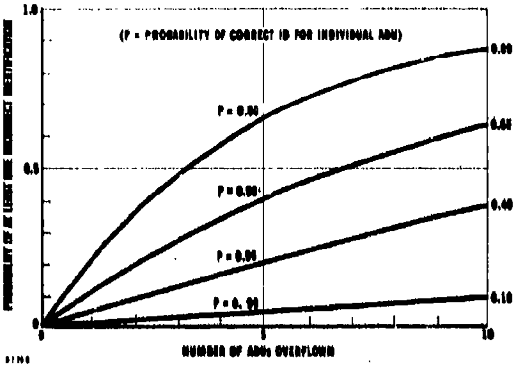


Figure 2. PROBABILITY OF AT LEAST ONE INCORRECT IDENTIFICATION BY AN AIR DEFENSE UNIT (ADU) OPERATOR VERSUS THE NUMBER OF ADUS OVERFLOWN

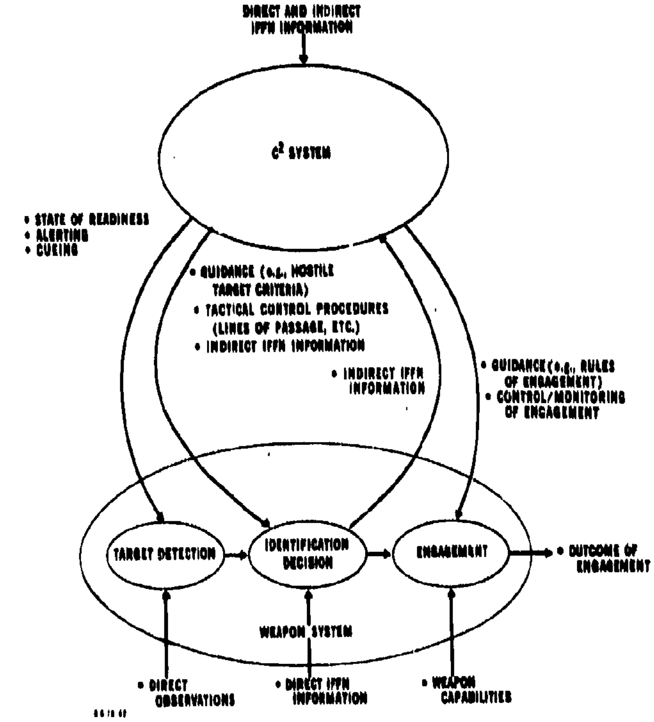


Figure 3. RELATIONSHIP BETWEEN C^2 SYSTEM AND WEAPON SYSTEM IN THE ENGAGEMENT OF AIRBORNE TARGETS

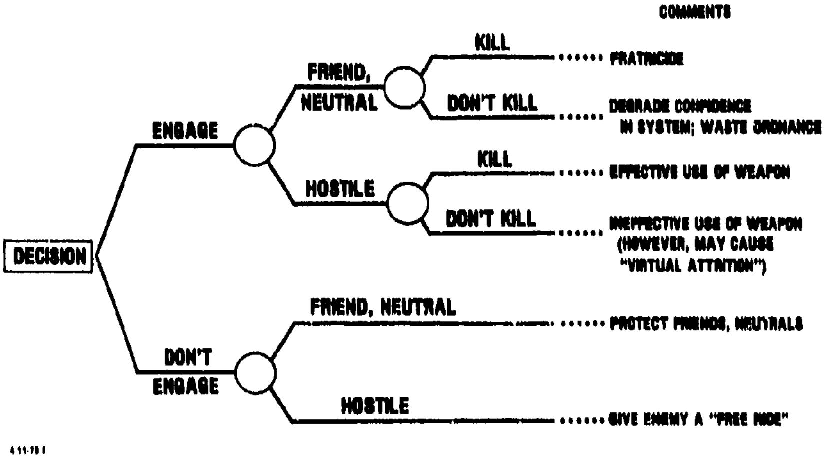


Figure 4. POSSIBLE OUTCOMES OF ENGAGEMENT

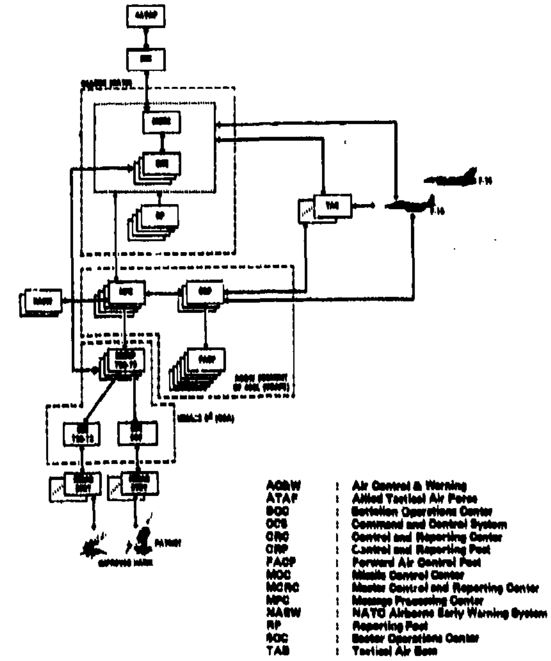


Figure 5. RELATIONSHIPS BETWEEN SELECTED COMMAND AND CONTROL FACILITIES AND AIR DEFENSE WEAPON SYSTEMS IN 4ATAF: 1983

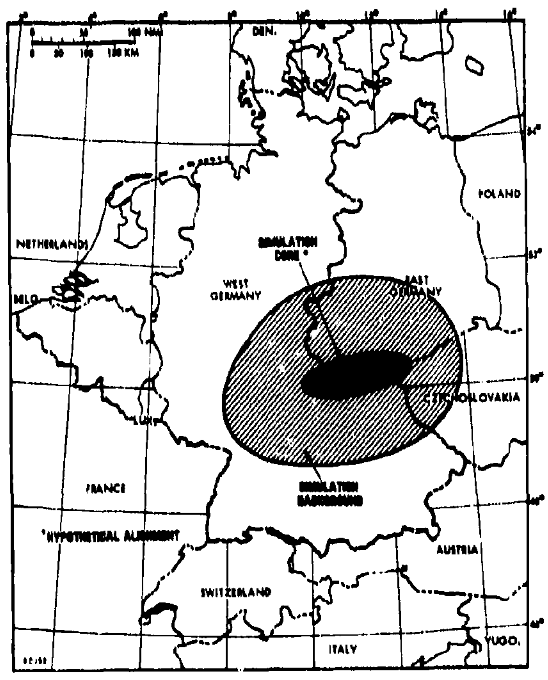


Figure 6. ARENA OF ACTION SELECTED FOR IDENTIFICATION TESTBED (DENOTED BY SHADED AREA)

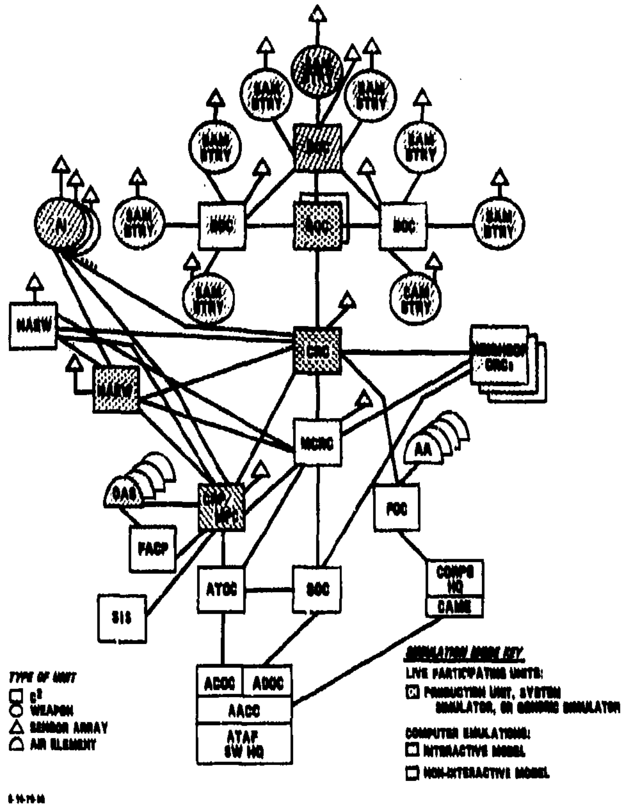


Figure 7. MODES USED TO REPRESENT NATO FORCES

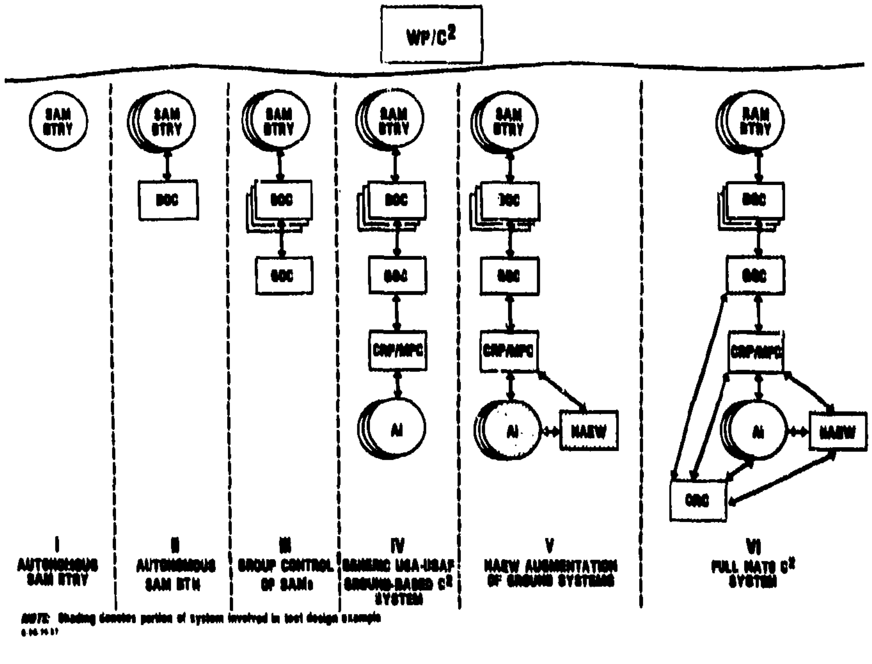


Figure 8. PROPOSED TEST PROGRESSION FOR IDENTIFICATION EVALUATION

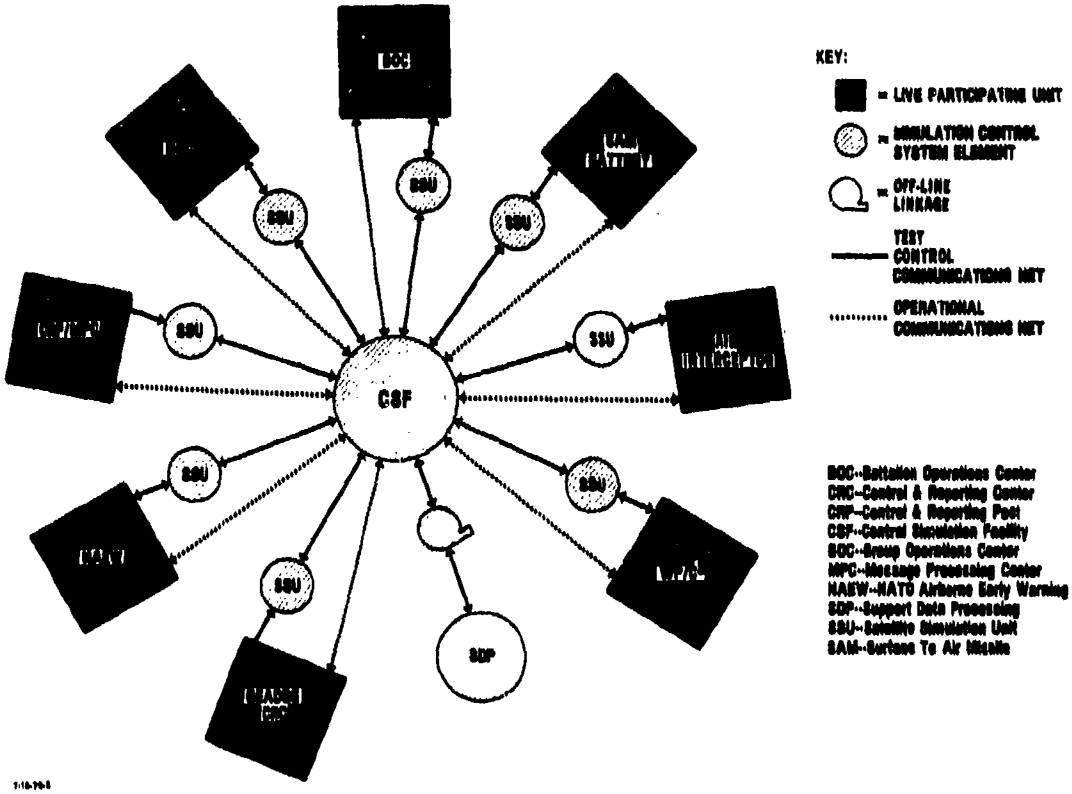


Figure 9. ARCHITECTURE FOR THE CENTRALIZED CONTROL TESTBED CONCEPT

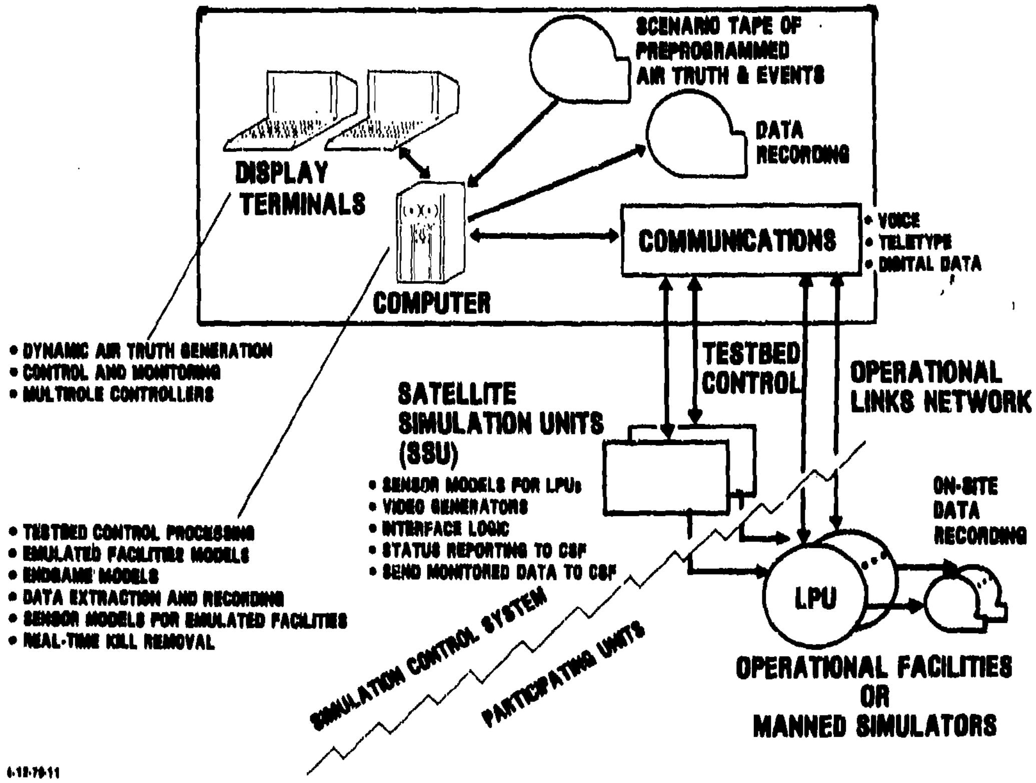


Figure 10. SIMULATION CONTROL SYSTEM FUNCTIONAL ELEMENTS ASSOCIATED WITH TEST OPERATION ACTIVITIES

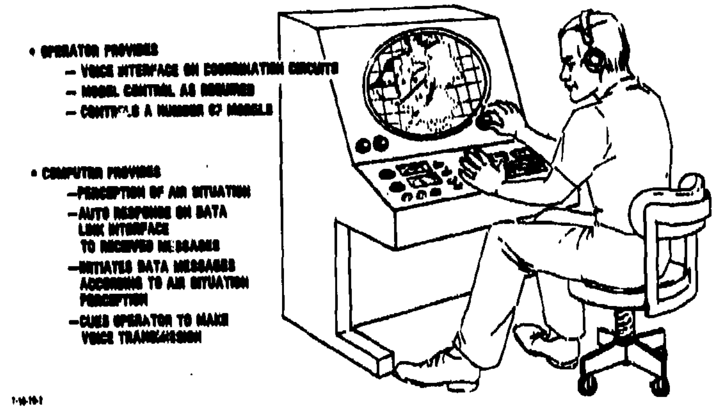


Figure 11. MANNED INTERACTIVE EMULATED FACILITIES MODELS--CONCEPT OF OPERATION

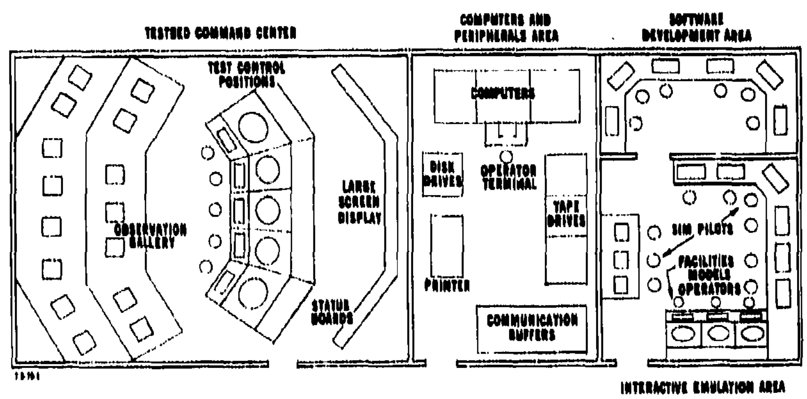


Figure 12. CENTRAL SIMULATION FACILITY LAYOUT

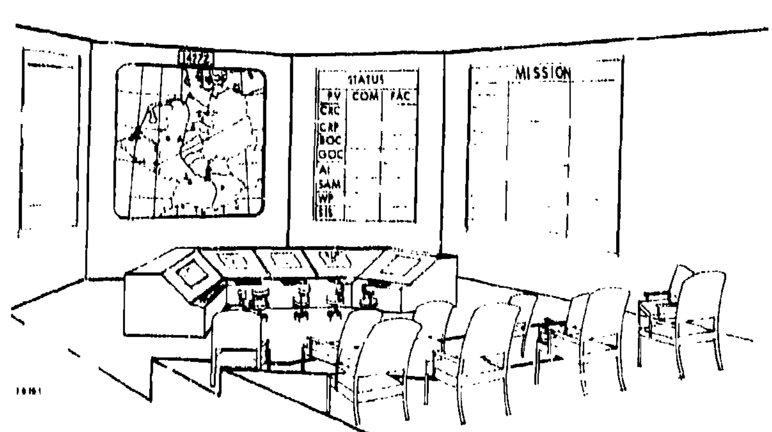


Figure 13. TESTBED COMMAND CENTER

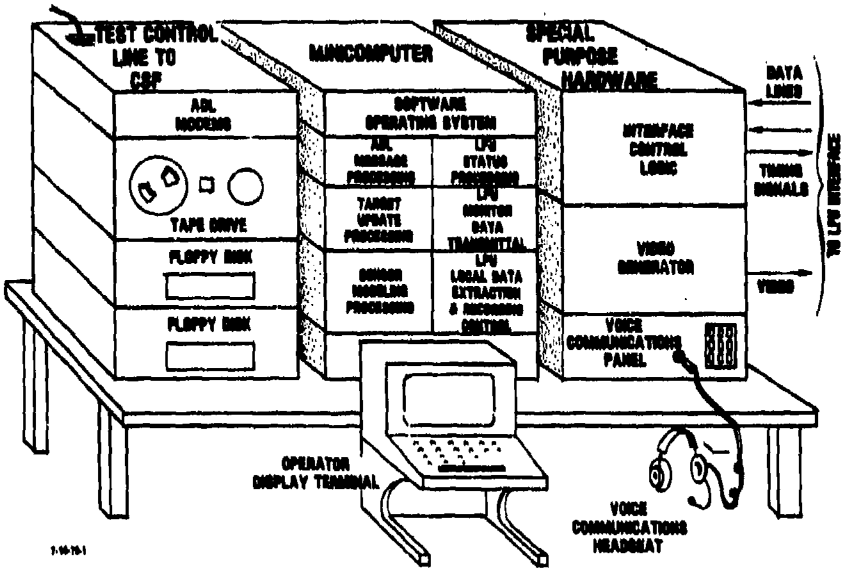


Figure 14. SATELLITE SIMULATION UNIT (SSU) COMPONENTS

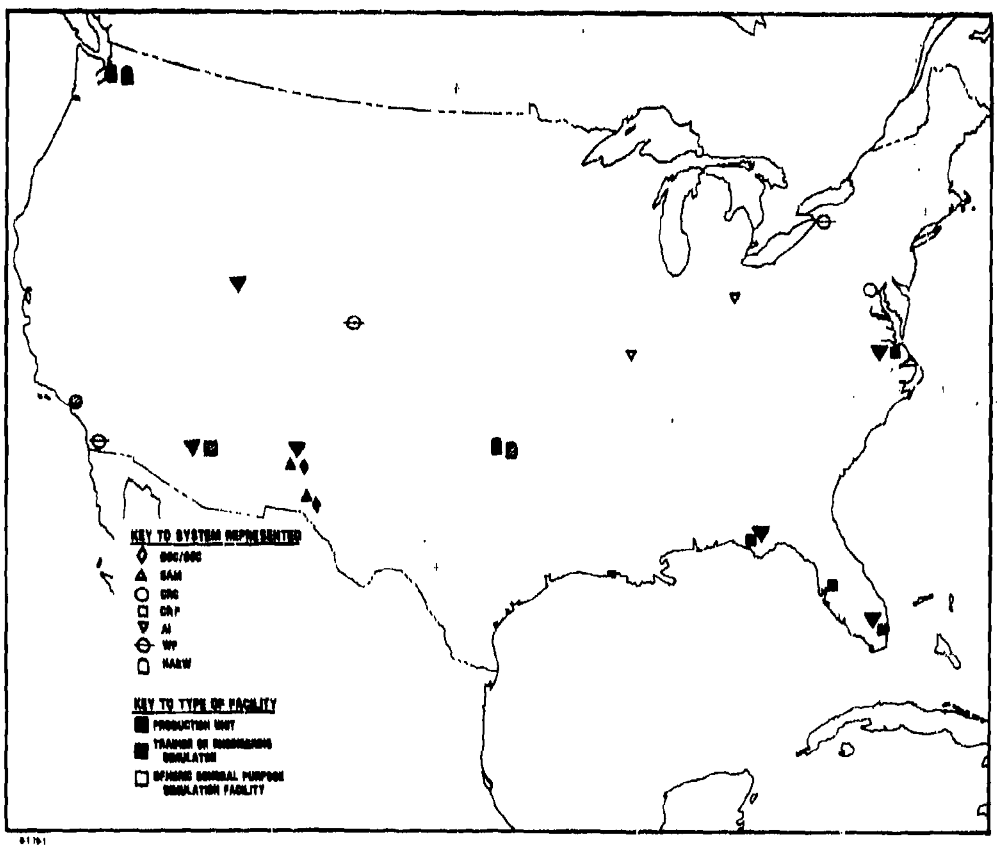


Figure 15. CANDIDATE FACILITIES FOR IDENTIFICATION TESTBED LUPS

AIR-TO-AIR ENGAGEMENT SIMULATION

Goetz Wunderlich/Roland Braun
Industrieanlagen-Betriebsgesellschaft mbH (IABG/SOL)
8012 Ottobrunn
Germany

SUMMARY

Since 5 - 10 years various one-versus-one air-combat models exist in several institutes and companies and are used mainly for comparison studies and trend analyses in the area of aircraft and weapon evaluation. Recent events (Southeast Asia, Middle East) have demonstrated clearly that there are usually more than two aircraft in the combat arena. Therefore German-MOD decided to develop a multi-dual-model which considers the aircraft, its avionics, armament and the pilots behavior. Of great importance is the attachment algorithm that allocates the opponents on the basis of active and passive threat values.

Another very important part in air-to-air engagement is the phase prior to combat, consisting of fighter allocation, combat air patrol (CAP) / ground controlled intercept (GCI) capability, influence of early warning etc.

To gain a high amount of flexibility a "two-stage" solution seems to be most promising. Preliminary computations based on certain scenarios will be performed with CAP- and GCI-models (step 1), producing data concerning geometry, fuel- and armament status, altitude, speed, heading, knowledge of enemy strength and capabilities etc., which will be used as input for the combat models (step 2).

1. INTRODUCTION

An important factor in airborne weapon system evaluation, especially in the early definition phase, is the calculation of probabilities of survival and success with respect to an expected threat. Therefore producer and user of combat aircraft and armament are looking for appropriate methods to calculate the qualification for combat, in other words the ability to survive an attack of a hostile fighter and to counter the enemy.

Despite many existing 1-vs-1 dogfight models and manned simulators it was found to be attractive to develop a m-vs-n air combat model which includes airplane, avionics, armament and pilot behavior and also takes into account the pre-engagement phase, i.e. fighter allocation, CAP/GCI-capability etc. These methods will be described in the following paper.

2. GENERAL INFORMATION

As mentioned above both, allocation and combat phase, should be covered by this method. To keep the instrument flexible a "two-stage" solution seemed to be most promising. Preliminary simulations based on certain scenarios will be done with CAP- and GCI-models (step 1), producing data such as geometry, fuel- and armament status, altitude, speed, heading, information status etc., which will be used as input for the combat model (step 2).

2.1 Fighter Control

2.1.1 General

Before starting the simulations (Fig. 1), assumptions and data concerning threat, early warning, airbase status and allocation planning have to be defined as input for the tactical employment procedure. The informations about the enemy are mainly gathered by autonomous detection or early warning messages. Search and detection may happen either in the pre-engagement phase or during the aerial combat itself.

Flying a GCI-mission the fighter will be guided to the point of potential air-to-air detection or a favourable weapon release point by groundbased or airborne control units. The fighter will activate its radar only when advised by the fighter controller and usually when detection or launch is promising. In contrary during a CAP-mission with various preplanned pattern the fighter operates its sensors permanently and searches for hostile targets autonomously.

2.1.2 Ground controlled interception

A GCI-computation for example, transfers the assumptions and data of fighter, target, airbase and allocation into suitable flight-profiles resulting in a certain final situation including or excluding detection. Those final situations are input to the m-vs-n air combat model SILKA.

An example (Fig. 2) may show how the GCI-model operates: Assuming an air defense fighter base, aircraft and armament performance data plus early warning informations, consisting of geometry and time delays. Various target tracks at the beginning of the simulation result in various target and interceptor positions at the missile launch point or detection point. These locations depend obviously on the early warning distance. Different early warning zones result in different interception zones. Those areas define the inter-

cept coordinates and the position, altitude, looking and aspect angles of the opponents calculating all possible intruder courses and various early warning distances the result is an early warning zone with a corresponding interception envelope. That means, GCI from this airbase is only possible in this particular interception area under the condition of certain early warning distances shown in the early warning (EW) area.

The combination of the results of separate airbases in combination with varying EW-distance and alert times ends up in corresponding geographical intercept lines which demonstrate how deep an enemy aircraft may penetrate under certain performance and information assumptions.

Besides the geographic situation it is of great interest how many interceptors can arrive at a certain location depending on EW-information and airbase situation as shown in Fig. 3 as a function of EW, target altitude and geographic coordinates. The columns representing possible number of fighters are to be considered as excluding each other. Each column represents one potential solution.

To show the application of GCI/CAP in the combined evaluation first let us have a look at a typical red counter air attack against targets in the vicinity of the western border of Germany.

A rather big formation is penetrating over German territory. Fighter bombers are escorted by a number of fighters. A stand-off racetrack jammer pattern is established to prevent early detection of the formation. At the splitting point the intruders are heading for their targets.

In this example (Fig. 4) four blue airbases are considered as fighter resources available. However, Neuburg in the south is too far away. Wittmund, Hopsten and Pferdsfeld, the remaining interceptor bases, are able to meet the threat. In this case GCI missions from Hopsten and out of a CAP pattern deployed from Wittmund are resulting in beam approaches, those from Pferdsfeld in a head-on attack.

2.2 Combat Modelling

The GCI- or CAP-calculations result in a set of geometrical conditions together with data on fuel and detection serving as input data for the combat models, especially the m-vs-n model SILKA. This model was developed during the last three years as a common activity of German aerospace industry and IABG.

2.2.1 Assumptions

The model is based on certain assumptions (Fig. 5).

Two assumptions which drastically effect the computers storage-capability and the computing time are related to time interval and number of participating aircraft.

Time interval:
Based on the experience of one-on-one models a time interval of one second is used, i.e. once per second the pilot makes a decision the aircraft performance and the geometry is calculated. Possible is also a separate time step for decisions (1 second pilot, 1/10 second missile) and flightpath (1 second aircraft, 1/10 missile); this option is in use.

Number of aircraft:
Based on the consideration that fast alerting, take-off and guidance of many fighters simultanously, very high take-off rates, coordinated take-off from various air bases seem to be unrealistic the number of blue interceptors was limited to four.

A red attack formation may consist of many aircraft, but it is assumed that a segmentation is possible. In this case not more than 26 aircraft (any escort/fighter-bomber combination) are involved in the simulated part of the air-to-air combat.

The segmentation for example allows to include escort fighters belonging to the following formation if they already detected the blue fighters or are called in by the engaged red formation.

Due to the rather small number of aircraft a relatively detailed modeling is possible. Splitting the number of engaging aircraft and skillfully changing the position (for example: result of the first simulation = input for the next simulation = next blue formation enters combat) the simulation of scenarios with many aircraft can be achieved.

Results:
The model is deterministic, for example, to pilot's decision and stochastic with respect to detection and missile effectiveness. Therefore it is necessary to run about 30 - 50 simulations (found by sensitivity tests) for reliable statistical results.

2.2.2 M versus N Allocation

The most difficult problem in m-on-n air combat - in reality as well as in the simulation - is the attachment of the participating aircraft. This will be explained in the case of three intruding red formations consisting of escorted fighter-bombers when attacked by 4 interceptors.

The task is to split up the initial "many on many situation" into very short "one versus one combats" with changing opponents. This is possible by using so-called "active" and "passive" threat values to allocate the aircraft to an attractive or threatening opponent (Fig. 6). It has to be pointed out that the entire situation is calculated new every second and the attachment is updated periodically. That means that the primary opponent can change every second if the resulting threat to or from a new hostile aircraft is greater than that in the step one second before. The resulting threat mainly consists of geometric and weapon threat (Fig. 7): The RANGE-THREAT, OFF-BORESIGHT- and ASPECT-ANGLE-THREAT. The value is ranging from O., that is "no threat at all", to 1., that is a "deadly threat".
Fig. 7 shows a possibility to define those components.

In this example a linear increase in range-threat was assumed from the detection range R_D to the shooting distance R_S and with a smaller increase finally to a certain value at zero range.

Regarding the off-boresight-angle (OBA), there is an increase from 180° to φ_S that means to the max. OBA for a certain weapon. From now on OBA-threat is 1.
The off-the-tail-angle (OTA) threat is similar except that there is already a certain amount at 180° if the weapon has all aspect capability. The dashed line shows OTA-threat for a different weapon with no front-hemisphere attack capability.
The variables R_D, R_S, φ_S etc. are special data for a certain missile.

The total threat is defined by multiplying those three components. The resulting threat is achieved when the tendency is calculated, depending on increasing or decreasing threat.

This weighting method simulates the extrapolation capability of the pilot.

To perform any type of defensive or offensive manoeuvre, the pilot has to select an appropriate opponent. This selection is made by evaluating the "threat matrix".
Fig. 8 shows a closer look at the blue threat matrix in that special example.
There are 4 blue AD-fighters, 4 escort and 3 fighter-bombers (FB).
For an offensive behavior we are considering the active threat, written in the horizontal lines.
Regarding the maximum active values for the first blue fighter, we find 0.8 against red 3 and red 6. Blue 2 sees 1.0 against red 6. Blue 3 0.7 against red 2 and blue 4 0.6 against red 7.

It is extremely important for a pilot to estimate the threat from the opponents against himself. We call this the passive threat. If it reaches a value in excess of a predefined threshold, the pilot gives up his aggressiveness and performs a defensive manoeuvre.
The passive threat can be read vertically in this matrix.
Blue 1 finds that of all the red A/C, red 1 threatens him most of all. Blue 2 looks at red 3. Blue 3 is anxious against red 5, and blue 4 against red 6.

But all the blue fighters have to consider that some of the red A/C may not be visible. So if we overlap the detection matrix, generated every second by the sensor subroutines, we see a substantial change in the active and passive threat relations.

The model pilot as well as the human pilot is actually able to remember the latest position of his target for several seconds. So it is not possible to "forget" the position of the target from one second to the other.

As mentioned before, the threat values are compared with certain predefined threshold values. These values affect the decision of the pilot, and are ranging between O. and 1.0 for events such as:
- emergency bomb release
- fighter-bomber defensive manoeuvre with bombs on board
- fighter-bomber defensive after offensive
- fighter defensive after offensive
- secondary opponent possible.

This last mentioned threshold is explained as follows:

Usually a blue fighter has a primary opponent e.g. the red escort. It could happen that the active threat against a fighter-bomber is equal or greater than the defined threshold. In that case the blue A/C switches to the new target that was originally of secondary priority.

Finally the splitting into 1 versus 1 duels is achieved. The mutual attachment of the A/C of the two parties is possible.

A very important problem is the selection of the proper weapon. Fig. 9 shows that if both, the short range (SR) and medium range (MR) missile could be selected, the SR missile has priority.
The maximum of medium and short range missile threat is weighted and called the resulting threat. To select the proper weapon the essential question is: Is a preselection defined? In the case of a semi active missile launched, succeeding radar illumination of the target is necessary. After the pilot is able to select a new weapon due to a new resulting threat.

2.2.3 Output

Besides the printout SILKA data concerning air combat history and missile events are written on tapes as input for off line programs. Especially in the development and test phase of the program plot and screen were very useful tools, because failures and unfortunate decisions of the model can easily be located and changed.

The example (Fig. 10) generated by the SILKA plot program shows the history of a combat of 4 blue interceptors, 4 red FB and 4 red escort-fighters. To achieve a sufficient combat time, the kill probability of the missiles was artificially reduced to 25 %.

The initial phase of that particular fight is shown on Fig. 11 demonstrating the screen output on a graphic display. Around the 3-dimensional combat air space which is possible to be rotated around 3 axes, various details of the combat are visible, for example range, OTA, OBA, threat matrix, attachment matrix etc.

25 seconds later the lower part of Fig. 11 was taken from the screen. Demonstrated is the rotation of the 3-dimensional space, the flight history of the surviving opponents for the last ten seconds, the present geometric data and some additional details of the fight.

2.2.4 Application

There are many types of results offered to be used depending on the individual study purpose, e.g. missile specific trends or air combat attrition etc. In many cases, for example (Fig. 12) the launch geometry is an interesting result for a missile designer as well for the operator as they can be utilized to define max./min. range, off-boresight- and all-aspect-capability, inrange computation etc.

On the other hand combat attrition is the most important result. During first studies it was found out to be very helpfully not only to look at a "final result" i.e. result at a certain time limit, but also to look on the time history of the engagement to get an impression how attrition rates decrease or increase during combat time. This is shown on Fig. 13. There is an engagement of 4 A/D-fighters with a threat consisting of 4 fighter-bombers escorted by 4 fighters. Obviously the blue side had a superiour armament. This is shown by two facts: First the relatively low blue attrition compared to red and second the first launches which correspond with the time starting the red/blue losses. This combat ends with about 30 % blue losses. If we make the assumption, that, due to the fact that they are over enemy territory and relatively short on fuel, red escorts will not continue fighting if blue fighters want to leave the arena, it is possible to get a rather different type of interpretation: If the blue side would terminate the engagement at 10 % blue losses for example, they would gain nearly the same escort losses, about 70 % mission kill (compared to 90 % in the other case) and about 30 % fighter-bomber losses (compared to 70 %).

That means they may optimize their decision of terminating the engagement.

Fig. 14 shows the effect of force size: The red force has increased from 4 FB + 4 escort to 10 FB + 10 escort. This increase results in the indicated loss changes. Blue losses increase rapidly by about 200 % while red losses, mainly the fighter-bomber kills decrease in the same percentage. Again the effect of "optimized" engagement termination is shown: After T = 110 sec red attrition only moderately increases while blue losses change from 50 % to 80 %.

Corresponding to attrition curves Fig. 15 show the missile consumption, i.e. missiles fired and missiles lost that were still on board of shot-down-aircraft. In this case it came out, that in the medium range case about 40 % of the missiles were fired, about 20 % were lost on board and in the short range area about 25 % were fired, about 25 % were lost. Increasing the red force both missile firing and losses increase rapidly.

The next example (Fig. 16) shows the effect of a red stand-off-jammer: Red losses decrease by about 10 %, blue losses increase from about 10 % to 25 %, i.e. an increase by a factor of 2.5.

3. CONCLUSION

The models now have reached a first status to be used in production runs for studies. Before application a lot of tests, including sensitivity tests, force size/force mix tests, missile and avionik specific tests (multiple-target engagement capability, various inrange-options, active/passive fire control etc.) were performed. Furthermore it is planned to run validation tests in comparison to flight trials to increase the confidence level of a very new evaluation instrument. Up to now the program was used for in house purposes of the German aviation industry and at IABG for two missile-specific studies of the Federal Ministry of Defense concerning to-day-missiles, avionics, and next generation missile concepts.

It will be used in future air-defense studies as a flexible tool opening the possibility to evaluate the effectiveness of airborne air-defense systems concerning the influence of aircraft, armament, avionics, guidance, missions etc. in multiple air-to-air engagements.

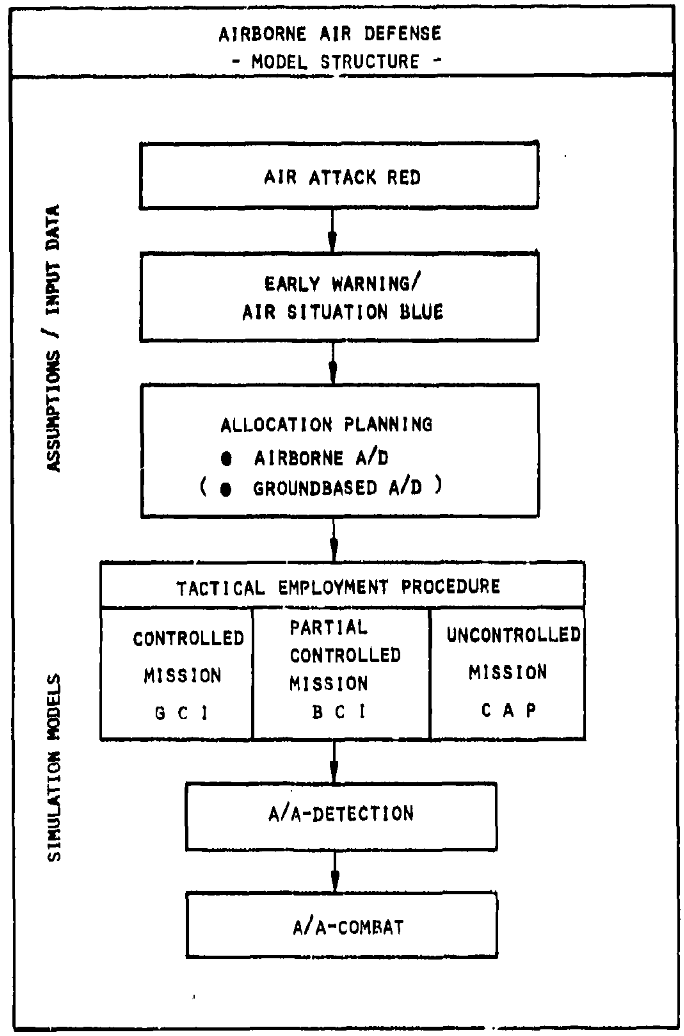


Figure 1

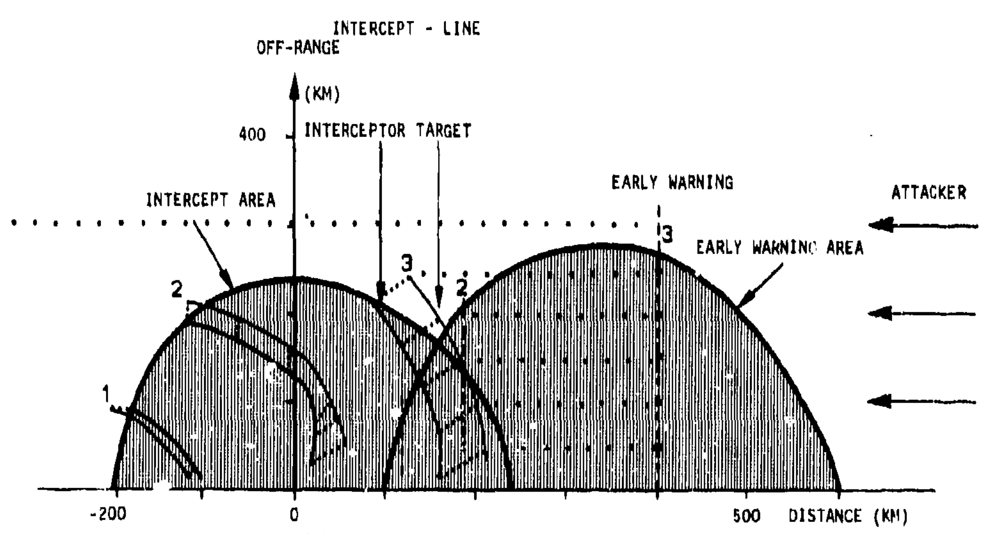


Figure 2

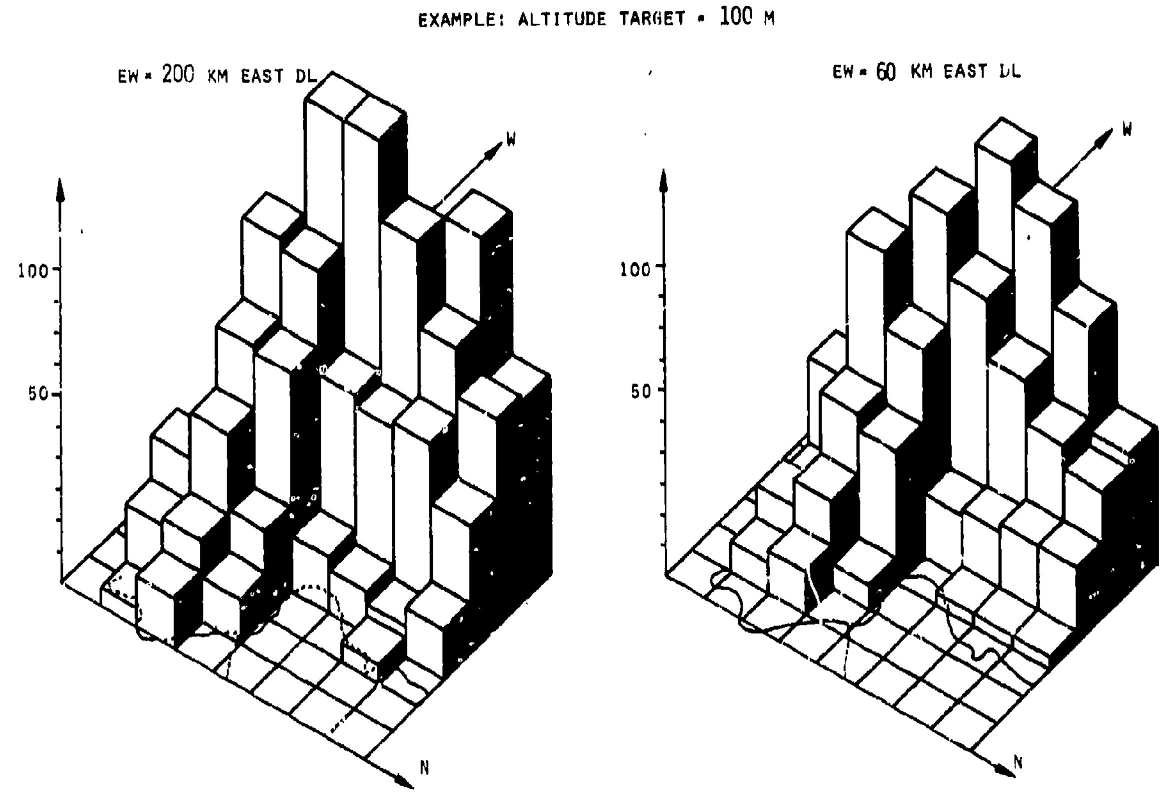


Figure 3

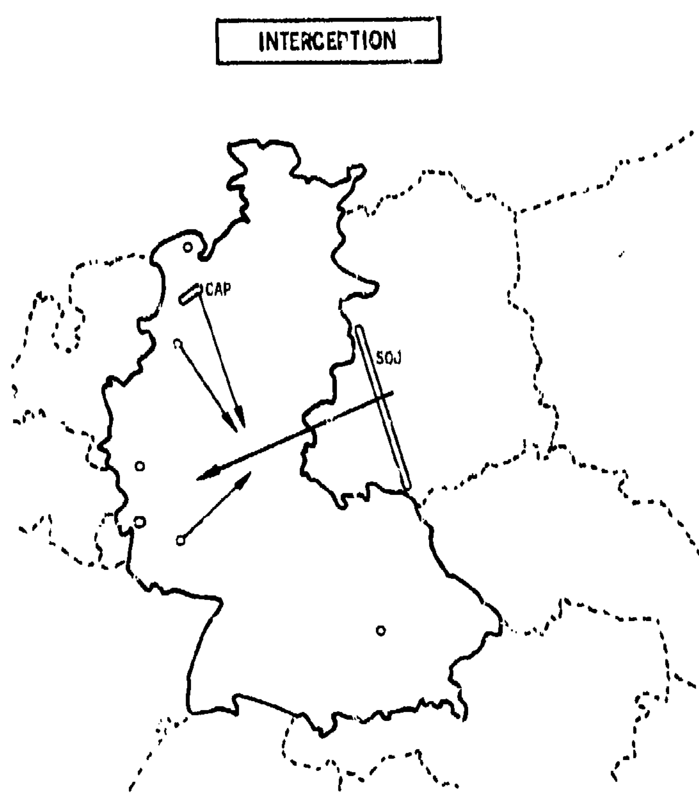


Figure 4

ASSUMPTIONS

- MAX. 4 AD-FIGHTERS
  MAX. 26 OPPONENTS (FB, ESCORT)
- SAME TACTICAL PRINCIPLES FOR BOTH SIDES
- STEPS OF 1 SEC
- DETERMINISTIC MODEL
- KNOWLEDGE OF A/C- AND MISSILE PERFORMANCE BLUE/RED
- STARTING GEOMETRY, FUEL, FORMATION ETC. HAVE TO BE CALCULATED IN PRELIMINARY RUNS (GCI, CAP)
- VARIOUS A/C, MISSILES AND AVIONICS
- FAST RUNNING MODEL (CYBER 175: $\frac{CT}{FT} \cong \frac{1}{3}$)
- STATISTICAL RESULTS

Figure 5

ATTACHMENT

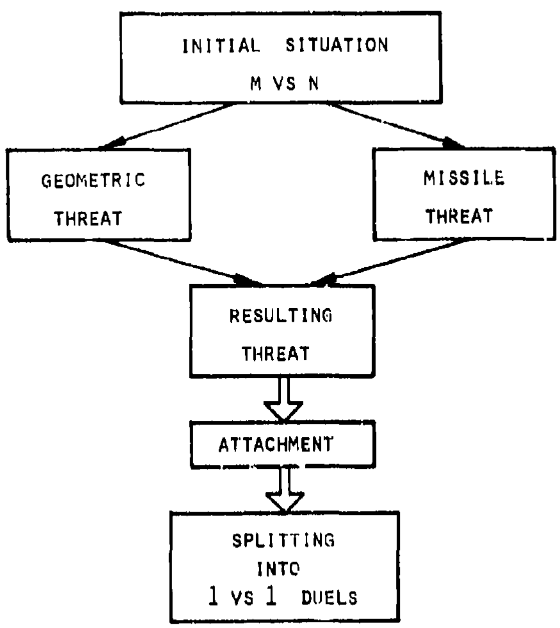


Figure 6

THREAT COMPONENTS

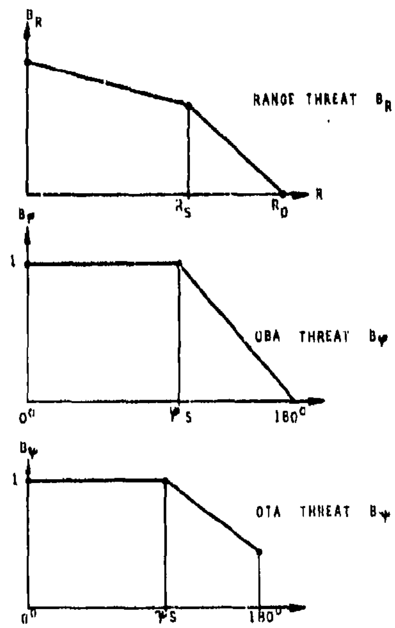


Figure 7

THREAT - MATRIX BLUE

	A/C-TYPE	A/C-NO.	BLUE AD-FIGHTER 1	BLUE AD-FIGHTER 2	BLUE AD-FIGHTER 3	BLUE AD-FIGHTER 4	RED ESCORT-FIGHTER 1	RED ESCORT-FIGHTER 2	RED ESCORT-FIGHTER 3	RED ESCORT-FIGHTER 4	RED FB 5	RED FB 6	RED FB 7
BLUE	AD FIGHTER	1					.3	.2	.8	0	.7	.8	0
		2					.5	.6	.9	0	.9	1.0	0
		3					0	.7	0	.1	0	0	.2
		4					0	0	0	.1	0	.2	.6
RED	ESCORT FIGHTER	1	.7	.6	0	0							
		2	.2	.3	0	0							
		3	.4	.9	.8	0							
		4	0	0	0	.3							
	FB	5	0	0	.9	0							
		6	0	.7	0	.8							
		7	0	.2	0	0							

AKTIVE THREAT

B1 ⟶ R3, R6
B2 ⟶ R6
B3 ⟶ R2
B4 ⟶ R7

PASSIVE THREAT

B1 ⟵ R1
B2 ⟵ R3
B3 ⟵ R5
B4 ⟵ R6

DETECTION-MATRIX

OVERLAPPED

AKTIVE THREAT

B1 ⟶ R6
B2 ⟶ R1
B3 ⟶ R7
B4 ⟶ R4

PASSIVE THREAT

B1 ⟵ R2
B2 ⟵ R1
B3 ⟵ R5
B4 ⟵ R4

Figure 8

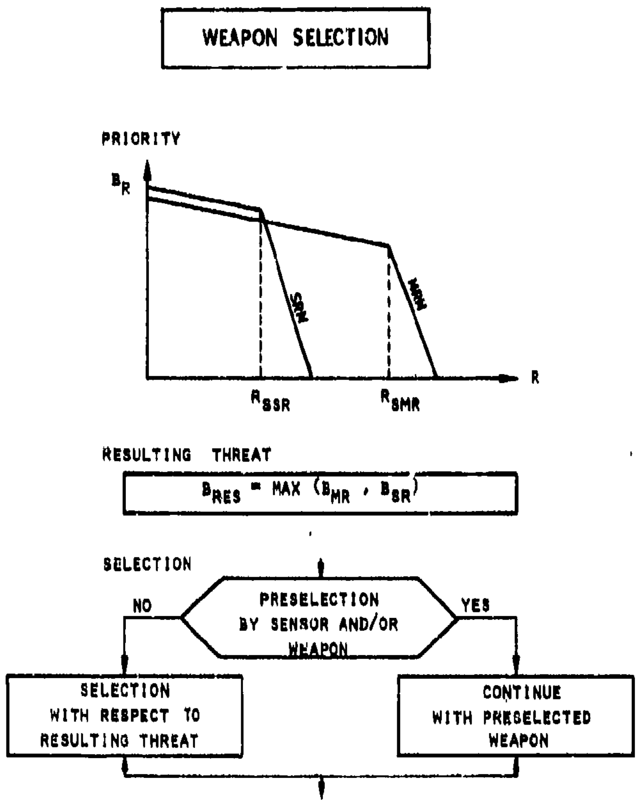


Figure 9

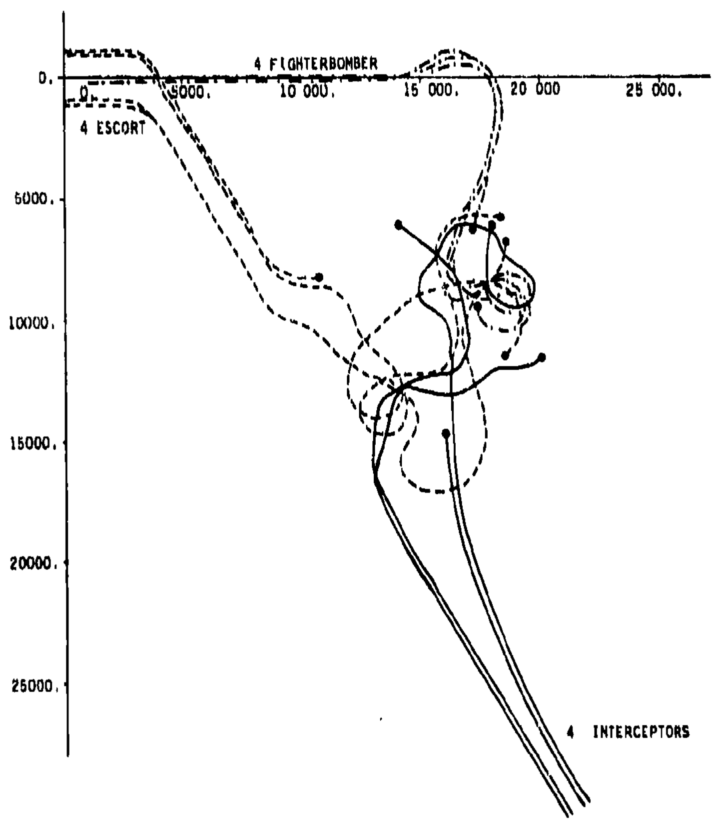
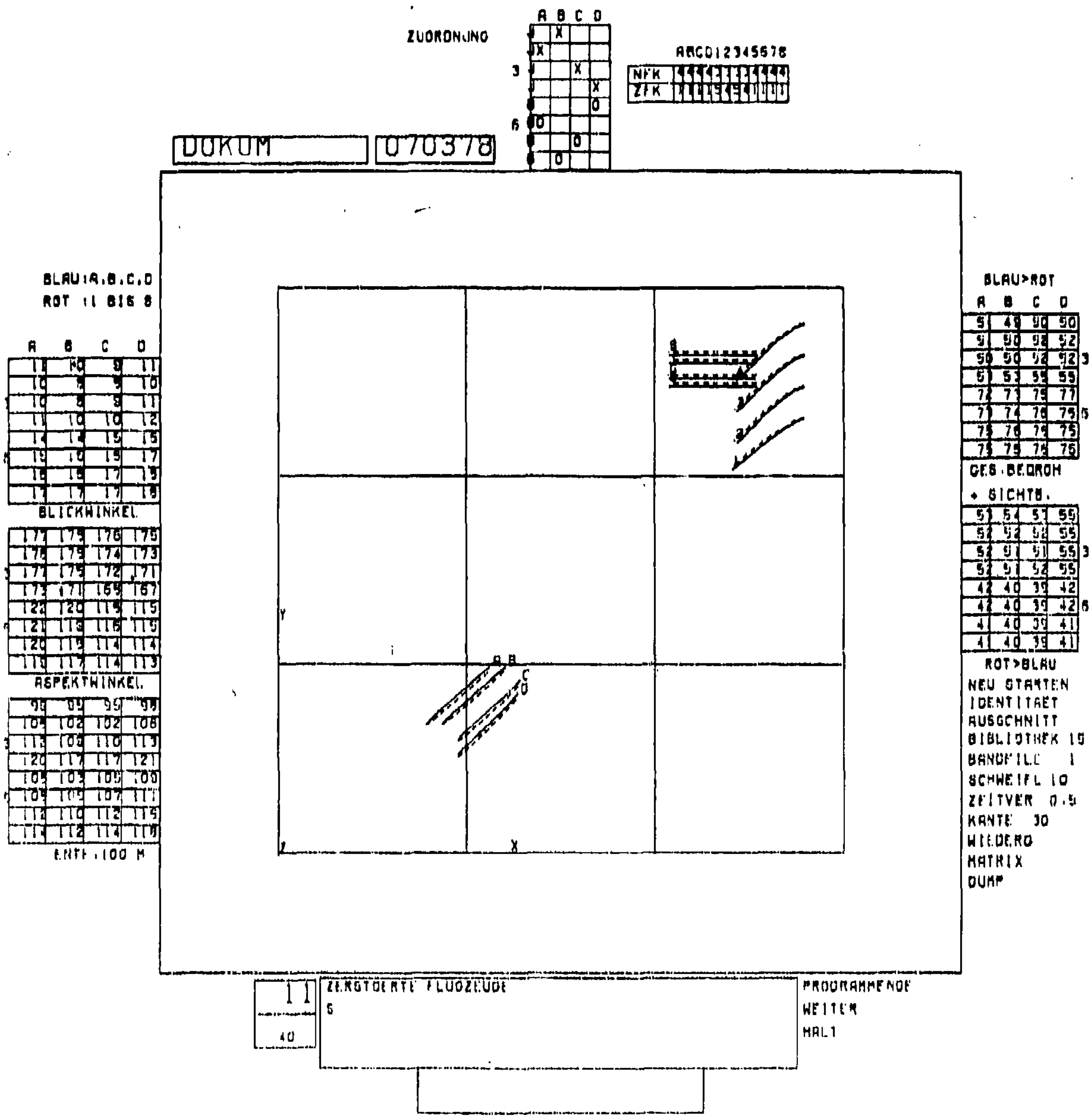


Figure 10



ZUORDNUNG
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BLAU:A,B,C,D
ROT 1 BIS 8
BLICKWINKEL
ASPEKTWINKEL
ENTF.100 M
BLAU>ROT
GES.BEDROH
+ SICHTB.
ROT>BLAU
NEU STARTEN
IDENTITAET
AUSSCHNITT
BIBLIOTHEK 15
SCHWEIFL 10
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KANTE 30
WIEDERG
MATRIX
DUMP
ZERSTOERTE FLUGZEUGE
PROGRAMMENDE
WEITER
HALT

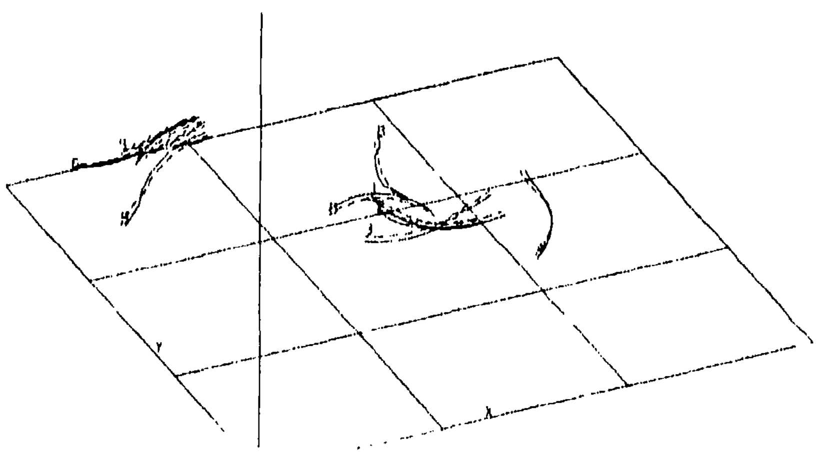

Figure 11

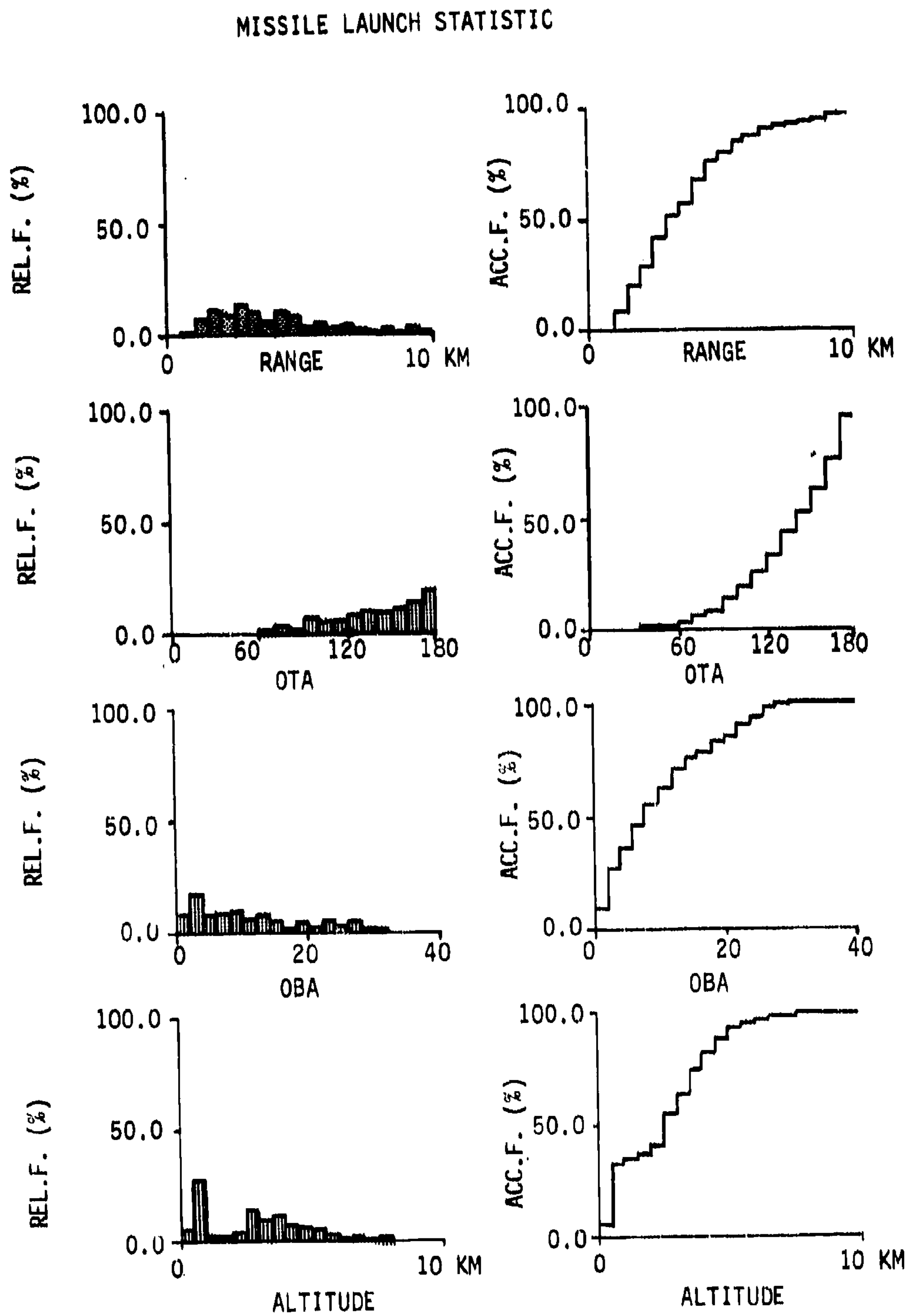
MISSILE LAUNCH STATISTIC
REL.F. (%)
ACC.F. (%)
100.0
50.0
0.0
RANGE
0
10 KM
OTA
0
60
120
180
OBA
0
20
40
ALTITUDE
0
10 KM

Figure 12

TYPICAL RESULT

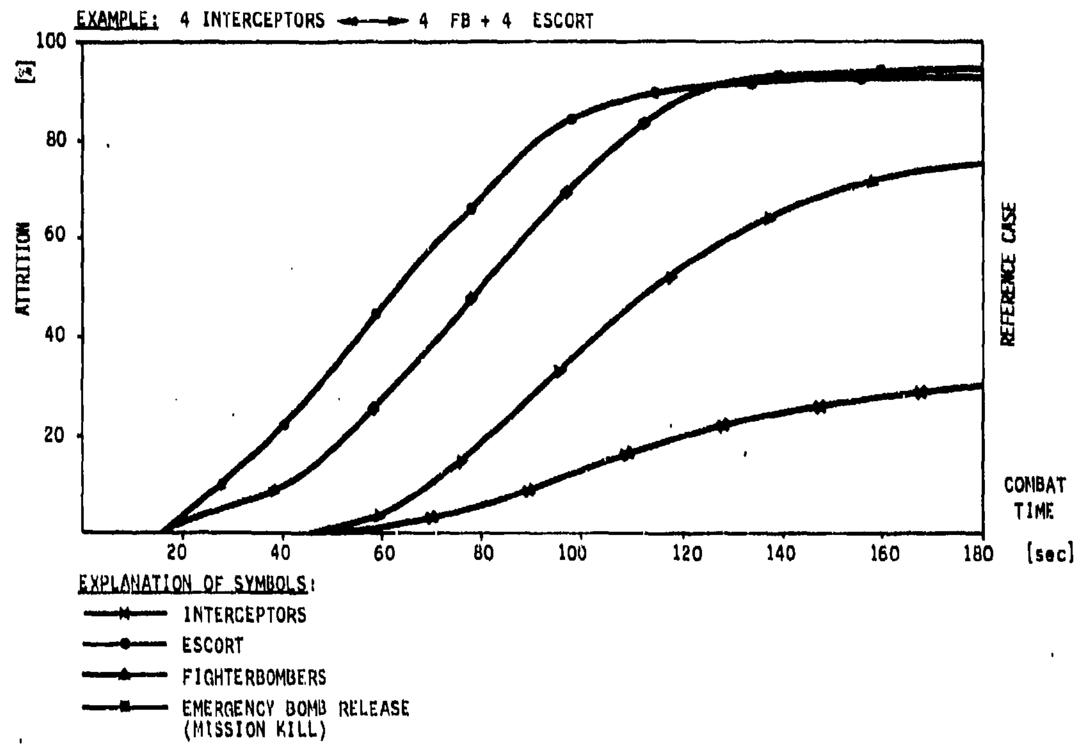

Figure 13

TYPICAL RESULT

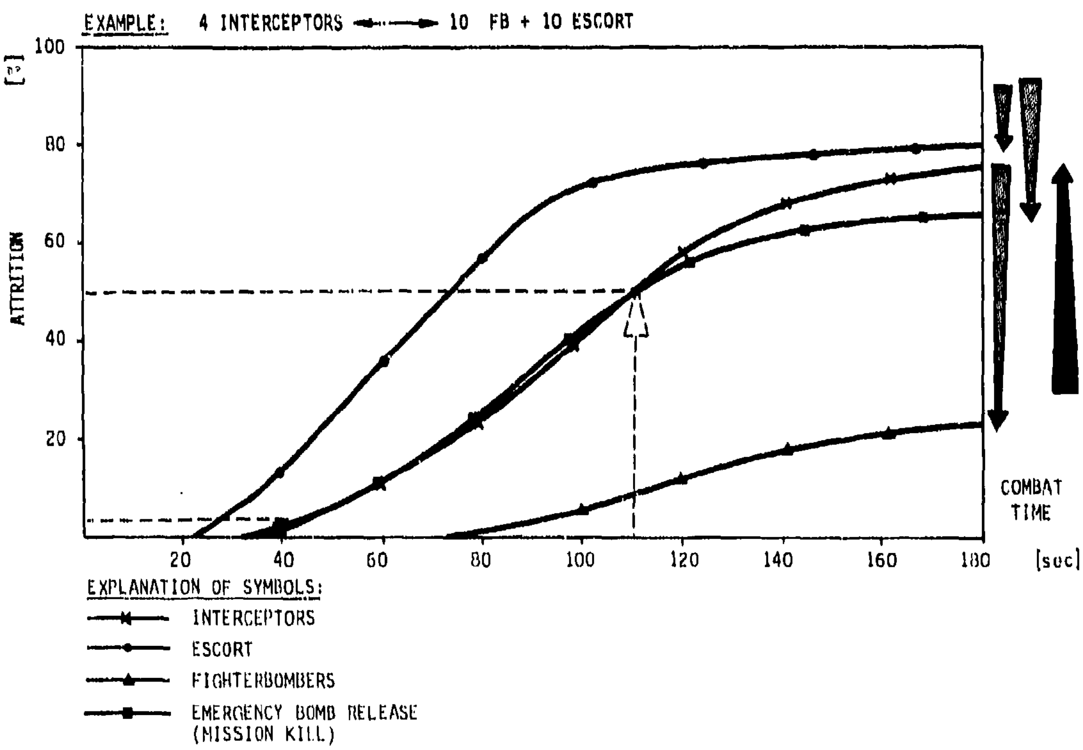

Figure 14

TYPICAL RESULT

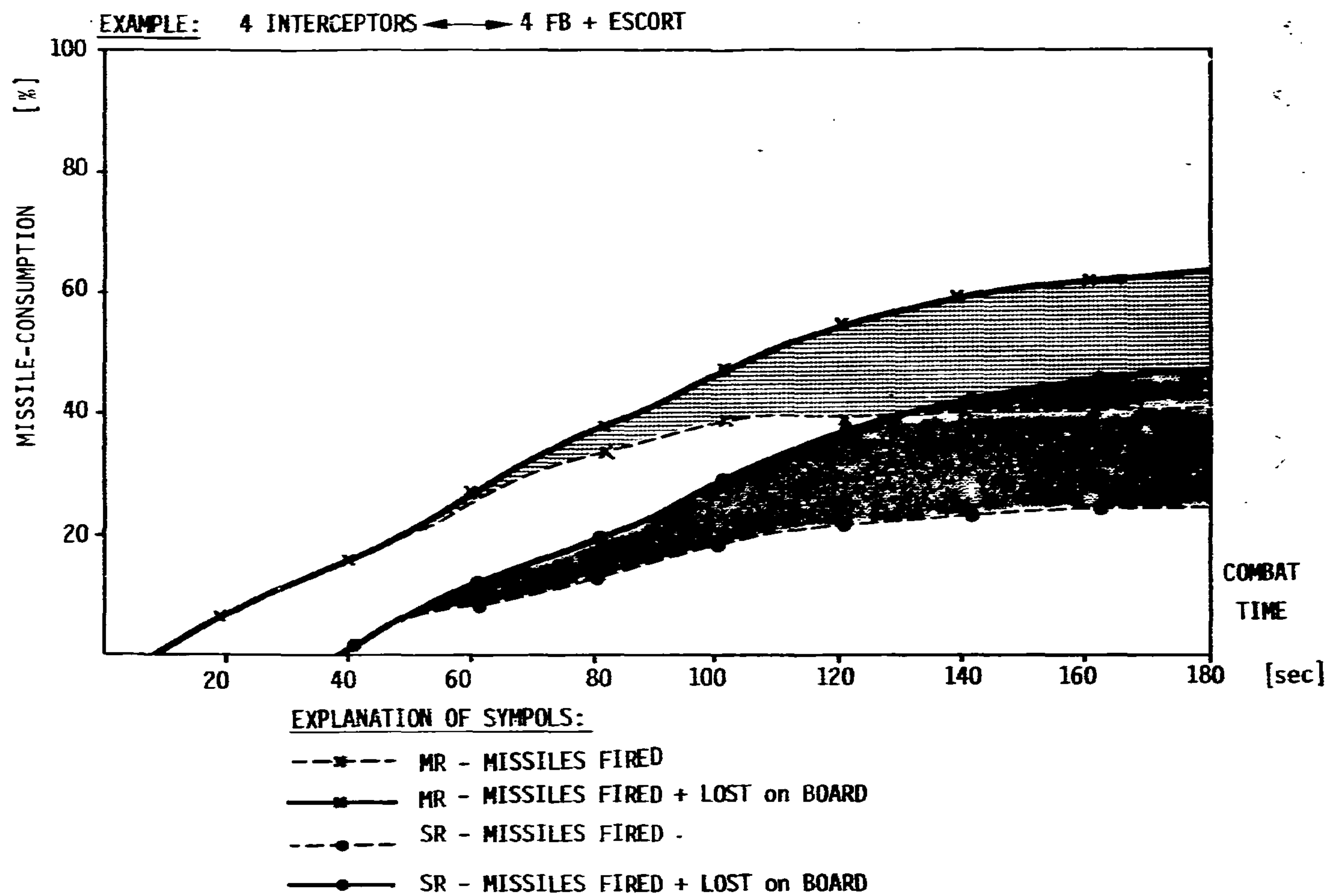

Figure 15

TYPICAL RESULT

EFFECT OF RED SOJ

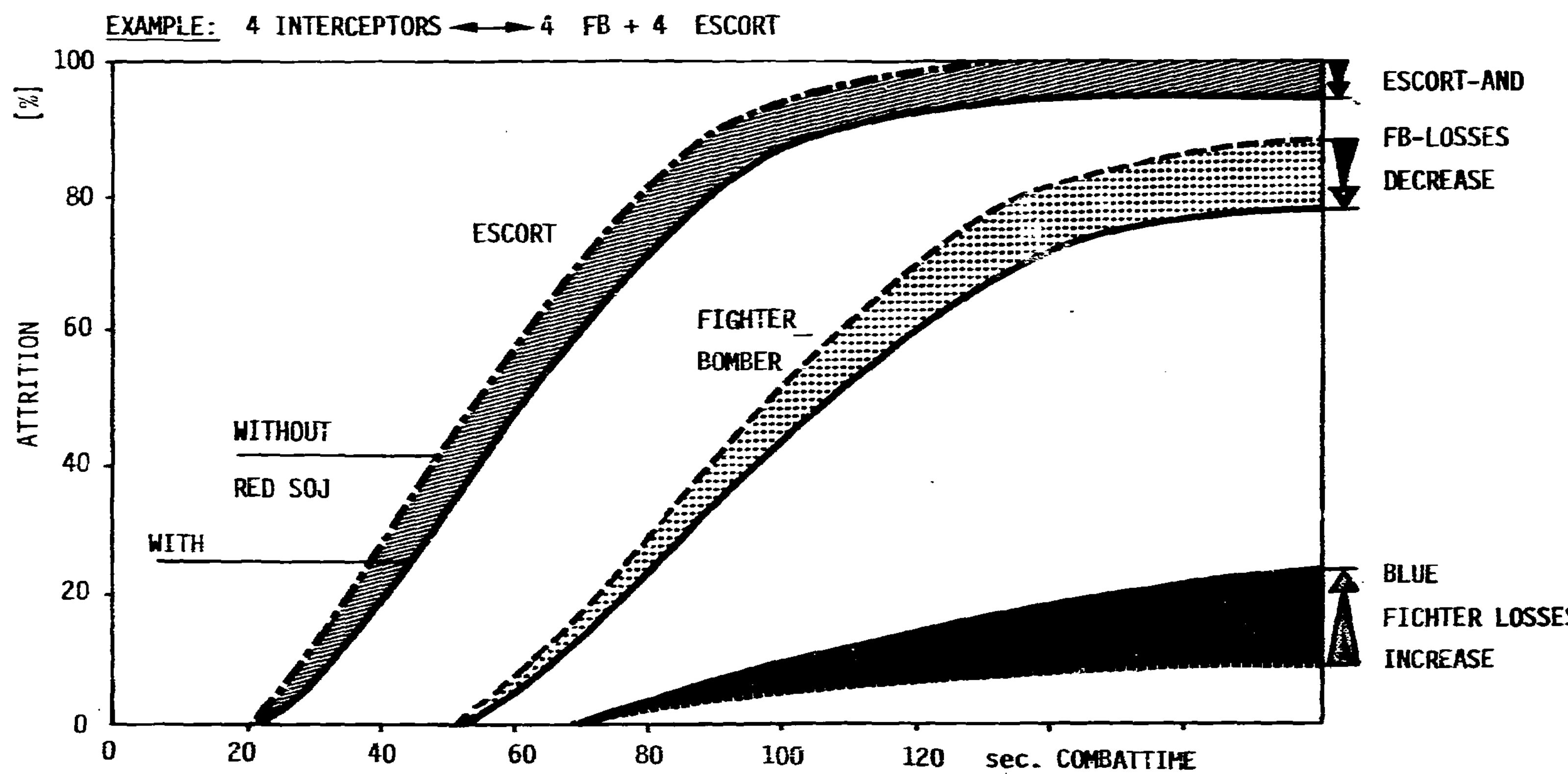

Figure 16

THE MITRE INTERACTIVE COMMUNICATIONS ANALYSIS PROGRAM (MICAP)

John M. Ruddy
The MITRE Corporation
Bedford, Massachusetts USA

SUMMARY

The MITRE interactive communications analysis program (MICAP), a user oriented computer program, can provide complex communications system performance and cost analysis. The program output, an "instantaneous" graphical presentation of the data, permits system synthesis and modification through rapid and easy system parameter iteration to obtain a desired system performance measure.

Satellite, airborne, or fixed relay communications systems can be analyzed. Software development has emphasized satellite communications systems analysis and synthesis, the primary use.

MICAP is designed to be used by communications system engineers through interaction with a set of program control, system definition, and analysis menus, which are defined in a hierarchical fashion. For example, the engineer can create a satellite communications system description by defining the terminal(s), satellite(s), signal structure, and propagation environment. The terminal(s) are defined by their location, motion (if any), and radio frequency and signal structure parameters. The terminals can be fixed, airborne, or shipborne. The satellite(s) are defined by their orbit(s), and transponder radio frequency and signal structure parameters. On-board signal processing as well as translating repeater satellite transponders can be analyzed.

The paper describes the program structure and capabilities, which in addition to the above, include cost/performance tradeoff analysis. Examples of modeling and prediction of satellite communication performance are presented. Applications to cost/performance tradeoffs and evaluation of architectural alternatives are discussed.

INTRODUCTION

The MITRE interactive communications analysis program (MICAP) is being developed to provide satellite communications system engineers with a convenient, easy-to-use, system analysis and synthesis tool. The primary driving forces in this effort are threefold. First, there is a need to approach the satellite system engineering process with a holistic viewpoint. That is, the space segment (satellites) and the terminal segment (earth stations) should be treated together in order to define cost-effective systems. This leads to the second consideration, namely, the need for including the system cost in performing system analyses, comparisons, and tradeoffs. Finally, there is a very real need for fast response in system analysis in order to meet schedule demands.

MICAP is a user oriented interactive program which is capable of complex system performance and cost analysis. The nature of the program output, graphical presentation of the data in the form of coverage maps and performance curves, also permits system synthesis to occur. This is accomplished by means of rapid iteration of system parameters in order to obtain a desired system performance capability. Although MICAP is also capable of analyzing airborne and ground fixed relay communications systems, the primary software development has been focused on satellite communications system performance and cost analysis.

MICAP has been specifically designed for use by communications system engineers through interaction with a set of program control, system definition, and system performance and cost analysis menus, which are defined in a hierarchical fashion. The engineer can create a satellite communication system description by defining the terminal(s), satellite(s), signal structure, and propagation environment in engineering terms. MICAP then provides, for a specified time or time interval, system geometry factors, such as satellite ground track, visibility contours, and elevation and azimuth angle from a specified terminal location. Many of these geometry factors can be associated with a variety of map projections which are selectable by the engineer. Performance analysis parameters, such as time delay, signal-to-noise ratio, R_{comp}, Doppler, data rate, or system link margin can be provided as a function of time. Any of the performance analysis parameters can be plotted on a map projection as a constant performance contour. For example, contours of constant signal-to-noise ratio (e.g., 10 dB, 15 dB, 20 dB) could be plotted on a cylindrical equidistant map projection of Europe for a specified satellite system. In addition to performance analysis, MICAP can perform rudimentary terminal cost analysis and tradeoffs. The satellite and overall system cost analysis capabilities have not yet been installed in MICAP.

This paper describes the overall MICAP software structure and analysis capability. A brief example of system modeling and prediction of satellite communications performance is included to illustrate the MICAP structure and capabilities.

MICAP SOFTWARE STRUCTURE

MICAP software has been developed with user needs and convenience high on the list of priorities. The user interacts with the system by sitting at a graphics terminal and communicating with MICAP through the keyboard as in figure 1. All communications are presented on the screen in alphanumerics and/or graphics. The graphics terminal used in the present implementation is a Tektronix 4014 configuration.

In addition to the terminal, there is a Tektronix 4631 Hardcopy Unit and 4923 Digital Cartridge Tape Recorder. The terminal is connected via hard wired modems (4800 baud) to the MITRE Corporation's IBM Model 3031 central processing unit (CPU), which has approximately six million bytes of storage. In addition, approximately 2400 million bytes of memory are available through the use of on-line disk drives. MICAP comprises approximately 40,000 lines of code and utilizes up to one million bytes of main memory. Operation is on-line using the general purpose interactive Time Sharing Option (TSO) of IBM's Multiple Virtual Storage (MVS) operating system.

MICAP software, which has been coded in PL/I, is interactive, non-real time and menu driven. It has been designed in a hierarchical fashion. This hierarchical approach, with predetermined software interfaces between the control program and other program options, permits the easy addition of new capabilities. This is shown representatively in figure 2. The user interacts with MICAP using the keyboard to access the control menu option. There are four basic types of menu option: (1) the control option menu, (2) file option menu (permanent and temporary), (3) display control option menu, and (4) computational or analysis option menus.

MICAP is designed to interact with a set of program control menus which are defined in a hierarchical fashion (tree structure). The top level tree is shown in figure 3. The default file, display parameter options, environment parameter option, and link parameter option are used to initialize the system parameters and conditions. The analysis parameter option contains the various analysis and computational suboptions which interface with the other options in order to perform the specified analysis routines. The user accesses the appropriate option by selecting one of the numbers associated with that option, as shown in figure 4. Figure 4 (which corresponds to figure 3) is exactly what the user sees on the graphics terminal screen when the MICAP program is loaded. Figure 4 and other similar figures in this paper are hard copies of what appears on the graphics terminal screen. They are obtained through the use of an attached Tektronix hard copy unit. A discussion of the various option and suboptions and their implications follows.

Figure 5 represents the next level down of the default file, display parameters, and environment parameters option menus.

DEFAULT FILE

The default file permits storage of parameters required to initialize a particular problem. Thus, the user needs to enter the data in the relevant menus only once. The set of completed menus is entered into a designated file by name. The entire file may then be recalled and modified, as necessary, during subsequent sessions with the terminal.

DISPLAY PARAMETERS & OPTIONS

This menu (figure 6) permits one to: (a) set up 3-dimensional displays, such as the cost graphs; (b) drive a remote drum plotter rather than use the hard copy unit; or (c) obtain a listing of the tabular data points used to generate any of the graphical displays (plot data edit option). The zero indicates that an option is not being used, whereas a one indicates that it is. All graphs and plots are automatically scaled and labeled.

ENVIRONMENT PARAMETERS & OPTIONS

This menu (figure 7) is used to describe the orbit dynamics environment and radio frequency (RF) signal environment.

Dynamical

The orbit programs include the capability to handle a non-spherical earth geopotential up to the J2 term. They do not yet handle on-line, luni-solar perturbations, but this can be accomplished with an extensive off-line capability.

RF

Ground noise can be specified by the user and included in the computation of satellite gain-to-noise temperature ratio (G/T). The effect of dry atmosphere on signal attenuation and noise temperature is included, using the so-called Dutton model. The effect of rain attenuation has not yet been included. Solar noise is included by treating the sun as a blackbody radiator and computing its effect on system noise temperature when the sun is in an antenna's field of view. The sun's emphemeris is computed as a function of time. Cosmic noise effects may also be included.

Figure 8 represents the next lower level of the link parameters & option menu and the analysis parameters & options menu.

LINK PARAMETERS & OPTIONS

The menu shown in figure 9 is used to define the system parameters for the particular communications problem being analyzed.

Antenna Pattern File

This menu permits the creation and use of 3-dimensional antenna gain patterns based upon measured or computed data. As an example, a 2-dimensional polar plot of a rotationally symmetric pattern is shown in figure 10. This is the actual Defense Satellite Communications System (DSCS) II area coverage receive antenna pattern, as measured. This file is used when mathematical representation of a parabolic or helix antenna is not appropriate.

Amplifier Transfer Characteristics File

This menu permits the use of actual transponder gain characteristics, relative to maximum repeater transmit power, in an end-to-end link computation. The DSCS II channel 2 transponder gain is shown in figure 11. The transponder gain includes the nominal uplink antenna gain and is relative to the output transmitter power level specified.

Terminal (Number)

These menus are used to describe location, dynamical behavior, and RF parameters of up to 16 terminals in a manner which then can be used directly by the various analysis routines. Examples of completed menus are shown in figures 12, 13, and 14. The upper bound of 16 terminals is arbitrary and can be increased if necessary.

Terminal Parameters. Used to name terminal, indicate whether terminal is to be included (1) or not included (0) in analysis, and to go further down menu hierarchy.

Terminal Location & Motion Parameters. Used to fully describe the terminal location and motion at a specified time (epoch).

Terminal RF Options & Parameters. Used to describe RF transmit and receive channels for terminal as well as modulation type. The program permits: (a) traveling wave tube (TWT) backoff in case of multi-carrier operation; (b) Doppler tracking if desired; (c) terminal antenna tracking or fixed pointing direction with the two pointing angles (azimuth and elevation) defined by the user; (d) use of an analytically computed parabolic dish antenna pattern, a helix antenna pattern, or a table look up (antenna pattern file); (e) choice of either analog (1) or digital (2) modulation class, phase or frequency coherent or non-coherent (1, 2, 3, 4) type, and 2-ary, 4-ary, etc. (2, 4, . . .) order. The program also allows the user to specify the overall system receive noise temperature or permit computation of system receive noise temperature using the actual or specified receiver chain noise temperatures, gains, and line losses.

Interlink (Number)

These menus describe up to 16 relay platform locations and their dynamical behavior (i.e., orbit or flightpath), type of repeater, and RF parameters in a manner which is directly usable by the various analysis routines. Examples of the menus and sample data are shown in figures 15, 16, and 17. Again the upper bound of 16 interlinks is arbitrary and may be increased.

Interlink Options & Parameters. (figure 15) Used to name interlink or relay (satellite, aircraft or fixed); indicates whether interlink is to be included in analyses, whether interlink is satellite or airborne relay (fixed), whether interlink repeater is a transponder type (translating) or regenerates signal (the transplexer option is not yet defined); defines transponder channel gain; and permits access to lo· · · levels of menu.

Airborne. Permits definition of location and motion parameters associated with the relay platform in a manner similar to menu shown in figure 13.

Orbital Parameters. (figure 16) Permits complete description of orbit with respect to a specified epoch, which in our case is referenced to the 1950 epoch January 0.0 The epoch line defines time of perigee.

Interlink RF Options & Parameters. Same definitions as for the terminal RF options & parameters (i.e., "mirror" image) in figure 14.

ANALYSIS PARAMETERS & OPTIONS

The top level menu for this portion of the program is shown in figure 18. The first three lines (1 to 3) are used to set the time period over which solutions are desired. Thus, there is a start time, a stop time, and the time steps for the solution desired. One may examine a problem over any time interval desired with as fine grain time resolution as deemed necessary. Setting equal start and stop times provides a single time solution.

Calendar Functions

This menu is used to define universal time epoch in Julian days, hours, minutes, and seconds, given east longitude and local mean solar time. The epoch is referenced to 1950 January 0.0.

Performance Factors

This menu is used to include the degradation effect on signal-to-noise when multiple terminals use the same satellite transponder channel.

Map Options & Parameters

This menu (figure 19) permits selection of map coordinates: cylindrical equidistant (figures 20, 21), orthographic (figure 22), or polar; whether a map of the world, CONUS, or none is desired; the viewing point in terms of latitude, east longitude, orientation angle, and altitude; the size of map with respect to terminal screen; the latitude and longitude grid resolution; and whether terminal sites should be delineated by a triangular cursor. Any of the map projections can be used in conjunction with the appropriate system geometry and performance analysis routines.

System Geometry Parameters & Options

This menu (figure 23) provides access to system geometry options.

Orbit Perspective. (figure 24) Provides a view of the orbit over the specified time interval as viewed from an earth fixed point. The figure shows three 12-hour elliptic orbits (64.3° inclination) plus two 24-hour (2° inclination) orbits. Note that the observer is at an earth fixed point located above 45° N lat. and -10° E lat. at an altitude of 300,000 km. The apparent path of the satellites is shown for a 24-hour period.

Interlink Ground Track. (figure 25) Provides a view of the subsatellite trace as a function of time. This could be on any of the three projections and could be an airborne repeater "subsatellite" trace as well. The figure is for the same orbit as in figure 24. The granularity through perigee is due to 10-minute step time.

Interlink Shadow Ground Track. Provides a track of the solar "shadow" cast by the repeater element as a function of time. This can be an important consideration for millimeter wavelength communications links.

Site Penetration. (figures 26, 27) Provides (for any uplink or downlink terminal) an elevation angle history (figure 26) or azimuth/elevation angle history (figure 27) of the satellite(s). The center of the azimuth/elevation plot is zenith, the top of the plot is north, and the concentric circles and radial lines are 30° apart. Thus, the outer circumference represents the nadir. These figures are for the same satellites as in figure 24.

Terminal Ground Track. Provides a ground track as a function of time for moving terminals on map projection of choice.

Ground Coverage Pattern. Provides contours of constant elevation angle for a fixed time or for a series of time points on a map projection of choice, all operator selectable. Figure 28 shows the 1° and 20° elevation angle contours for the four DSCS II satellites in their nominal locations.

Interlink Look Angle. Provides angular separation for two points located on the earth's surface, as viewed from any satellites or aircraft, as a function of time.

Sun and Moon Ephemeris. Provides azimuth end elevation angles as a function of time for sun or moon, given epoch.

Performance Analysis Parameters & Options

This menu (figure 29) permits the user to select which link performance parameters he wishes to analyze.

Performance Select. With this menu and selection of an uplink and downlink terminal pair, the user can evaluate: (a) up, down, end-to-end time delay (assumes zero processing time in repeater), (b) up, down, end-to-end signal-to-noise ratio (SNR), (c) R_{comp} for the specified channel; e.g., linear repeater, hard decision processing (HDP), soft decision processing (SDP), and decode-recode (DEP) processing, for M-ary orthogonal modulations, (d) DR_{comp}, the difference in channel performance between HDP, SDP or DEP and the linear repeater, (e) probability of error bound associated with R_{comp}, (f) up, down, end-to-end Doppler, (g) up, down, end-to-end energy-to-noise ratio (ENR) for a specified data rate, (h) probability of error given modulation, data rate, and desired margin, (i) data rate given desired probability of error, modulation, and margin, and (j) margin given data rate, modulation, and probability of error.

Antenna Pattern Footprint. (figure 30) Provides satellite antenna pattern footprint on map projection of choice, antenna pointing direction of choice, and gain controus of choice. In this case the area coverage receive footprint pattern (actual) of the DSCS II Atlantic satellite is shown with -6, -4, -2, 0 dB relative gain contours.

Antenna Skyprint. Provides terminal antenna pattern "skyprint" on elevation/azimuth polar plot, for antenna pointing of choice, and gain contours of choice.

Performance Function Footprint. (figure 31) Provides contours of constant time delay, SNR, R_{comp}, Doppler, ENR, probability of error, data rate, and margin on map projection of choice with contours of choice. Figure 31 illustrates contours of constant data rate for DSCS II for a specific channel state, modulation, and bit error rate. Any of the performance measures can be plotted in this fashion.

Cost Analysis Parameters & Options

This menu (figure 32) permits selection of various submenus in the cost analysis section. At present this section can set up cost data files, extract cost estimating relationships (CERs) for terminals, and examine cost/performance interrelationships for terminals.

Cost Data File. Permits user to read in extant files, define new files, review existing files, and extract any one of three forms of CER against the sample data. An example of a low noise amplifier cost file is shown in figure 33. The three forms of CER in use at present are shown in figure 34 and a sample CER extraction (form #3) for the low noise amplifiers is shown in figure 35.

Terminal Parameters & Options. Permits examination of the cost variation of a terminal as different engineering parameters are allowed to vary over preset ranges. An automatic search through this multi-dimensional cost space can be made to ascertain the lowest relative cost terminal configuration. An example of a 3-dimensional cost sensitivity analysis is shown in figure 36. This was done using a specific terminal cost model and terminal configuration. The antenna size was two meters and the operating frequency was 8 GHz. The cost represents only the RF portion of the terminal. The sensitivity to low noise temperature rather than transmit power level is apparent in the region of approximately $200^{\circ}K$.

EXAMPLE

An example based on an actual problem statement provides a brief exposition of the analysis capability of MICAP. It was desired to have a knowledge of where a ground mobile force (GMF) terminal could be located in Europe so that it could support either six or twelve 48 kbps digital telephone circuits back to Washington, D.C. The GMF terminal is the TSC-94 whose RF parameters are presented in figure 14. The Washington, D.C. terminal is an FSC-78 whose RF parameters are presented in figure 37. The satellite used is the Atlantic DSCS II located at $12.5^{\circ}W$ whose RF parameters are presented in figure 17. Other constraints were the use of channel 2 which implies the use of the area coverage receive antenna (pointed as shown in figure 30) and the earth coverage transmit antenna. The transponder gain state was specified to be -12 dB and the modulation was selected as uncoded QPSK. A bit error rate of 10^{-3} and a system margin of 4 dB had to be maintained. The basic result was presented in figure 31, which indicates two contours of constant performance for the conditions specified. The 288 kbps contour encloses an area where at least six telephone circuits could be sustained and the 576 kbps contour encloses an area where the twelve telephone circuits could be sustained. This entire computation including logon, menu completion, and analysis was accomplished in less than one hour of connect time and less than 300 seconds of CPU time! The answer to the question is provided in a form precisely as required by the system engineer, and includes the effects of atmospheric attenuation and tilt differential. If system changes, such as modulation changes, different transponder loadings, etc., are desired, they can be entered as simple modifications to the various menus where appropriate. The new results can be very quickly ascertained. Thus, by iterating over a range of system alterations, system synthesis occurs. When the effects on terminal costs are included, a preliminary indication of cost/performance tradeoffs can be provided. MICAP thus permits engineering design synthesis and analysis to occur where previously the sheer magnitude of the effort would be prohibitive.

CONCLUSIONS

MICAP provides rapid, repeatable, and accurate communications system analysis/synthesis results for a wide range of satellite (or airborne or ground fixed) system problems. Key questions concerning system geometry and RF (electrical) performance can be answered easily and swiftly without recourse to large amounts of manpower. Due to the interactive and graphical nature of the program, effective system synthesis can be accomplished through systematic iterations of system parameters. Comparisons of performance effectiveness within a wide range of communications system alternatives can be made quickly. The ability to perform top level satellite system performance/cost tradeoffs requires further development and refinement of satellite and related life cycle cost estimating algorithms. When complete, these algorithms will be simple to install because of the modular nature of the software. MICAP will not replace detailed system design efforts. Its primary purpose and utility is to develop a small number of reasonable alternatives which would be then subjected to analysis in greater depth.

ACKNOWLEDGMENT

The writer would like to thank C.A. Zraket, C.A. Fowler, and E.L. Key for providing the corporate support for this development. Appreciation is also due to W.T. Brandon, L.S. Billig, H.T. Cervantes, and L.R. Jeffery for their encouragement. Finally, the writer would like to acknowledge particularly the analytic and software skills of D.B. Fritz in the realization of MICAP.

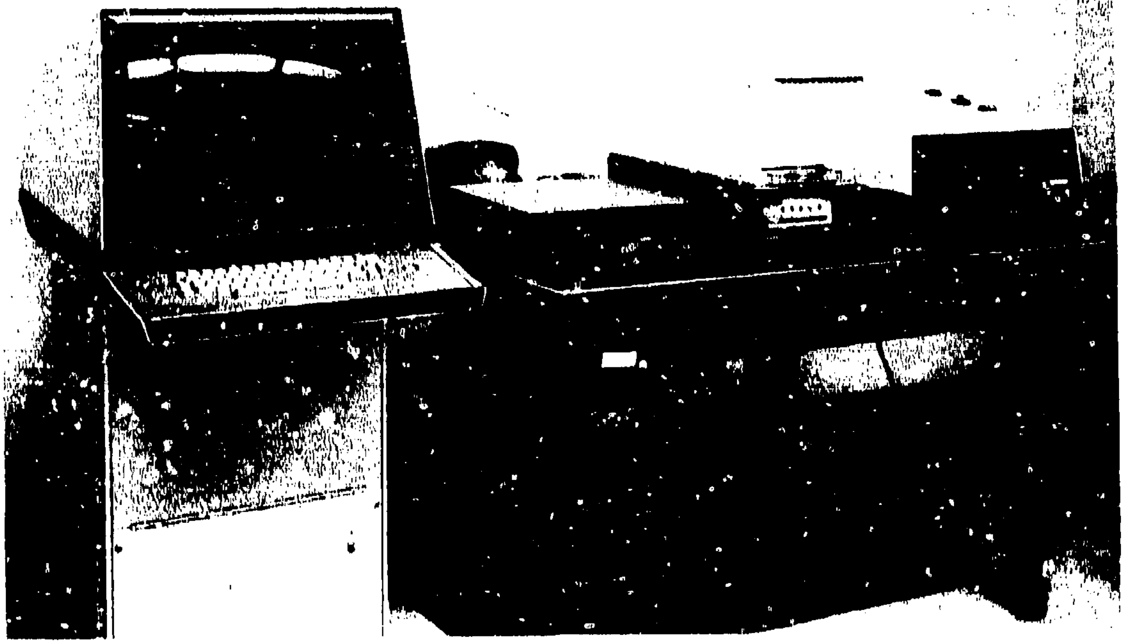

Fig.1 Graphics terminal

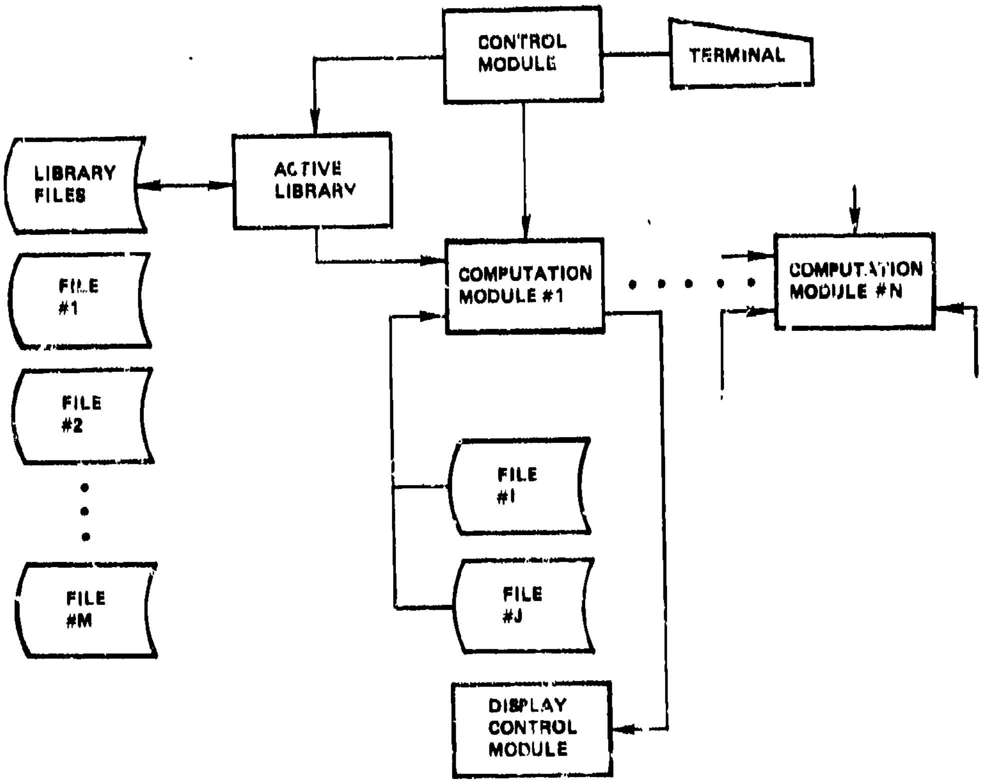

Fig.2 MICAP system overview

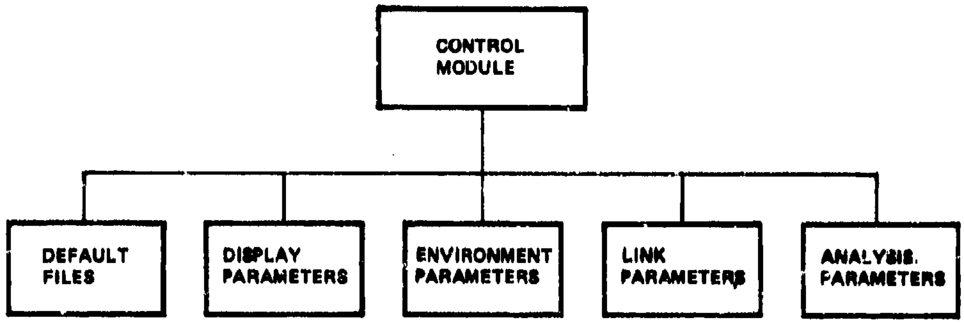

Fig.3 Top level MICAP control structure

```
CONTROL SELECT

    0 EXIT
    1 DEFAULT FILE                    DFTGMF
    2 DISPLAY PARAMETERS
    3 LINK PARAMETERS
    4 ENVIRONMENT PARAMETERS
    5 ANALYSIS PARAMETERS

MAKE SELECTION:
```

Fig.4 Top level control menu

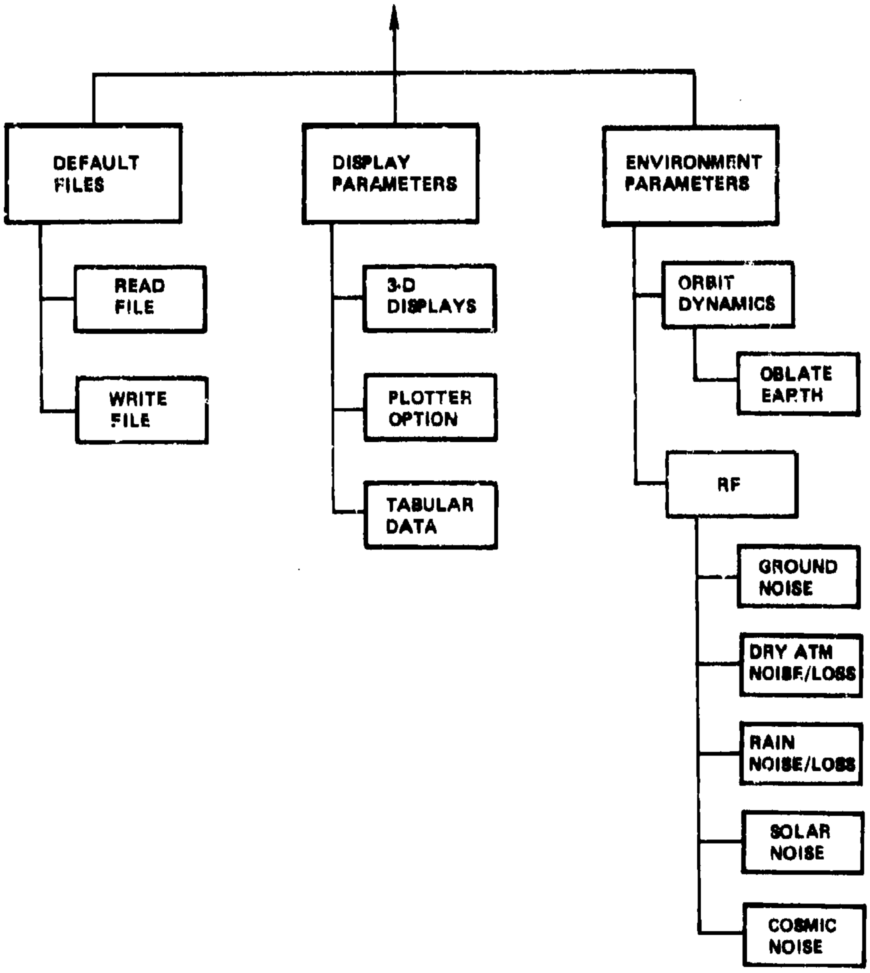

Fig.5 Lower level program control structure (partial)

```
DISPLAY PARAMETERS & OPTIONS

     0 NO CHANGE
     1 Y AXIS ANGLE (DEG)                      53.00
     2 Z TO X RATIO                             0.50
     3 Y DIRECTION LINES OPTION                    1
     4 FLOATING PLOT OPTION                        0
     5 X-Y AXES INTERCHANGE OPTION                 0
     6 CALCOMP PLOT OPTION                         0
     7 PLOT DATA EDIT OPTION                       0
     8 MITRE LOGO ANNOTATION OPTION                1

MAKE ANY CHANGE:
```

Fig.6 Display control menu

```
ENVIRONMENT PARAMETERS & OPTIONS

     0 NO CHANGE

     DYNAMICAL

     1 OBLATE EARTH OPTION              0
     2 LUNI-SOLAR PERTURBATION OPT      0

     RF

     3 GROUND NOISE OPT & TEMP (DEGK    0   0.0
     4 DRY ATM NOISE & ATTN OPTION      1
     5 WET ATM OPT (MM/HR,CM/YR)        0       0.0       0.0
     6 SOLAR NOISE OPTION               0
     7 COSMIC NOISE OPT, COEFF & EXP    0   0.0  0.00
     8 ATM AMP SCINT OPT & VAR (DB)     0       0.0
     9 ATM PHS SCINT OPT & VAR (DEG)    0       0.0

MAKE ANY CHANGE:
```

Fig.7 Environment definition menu

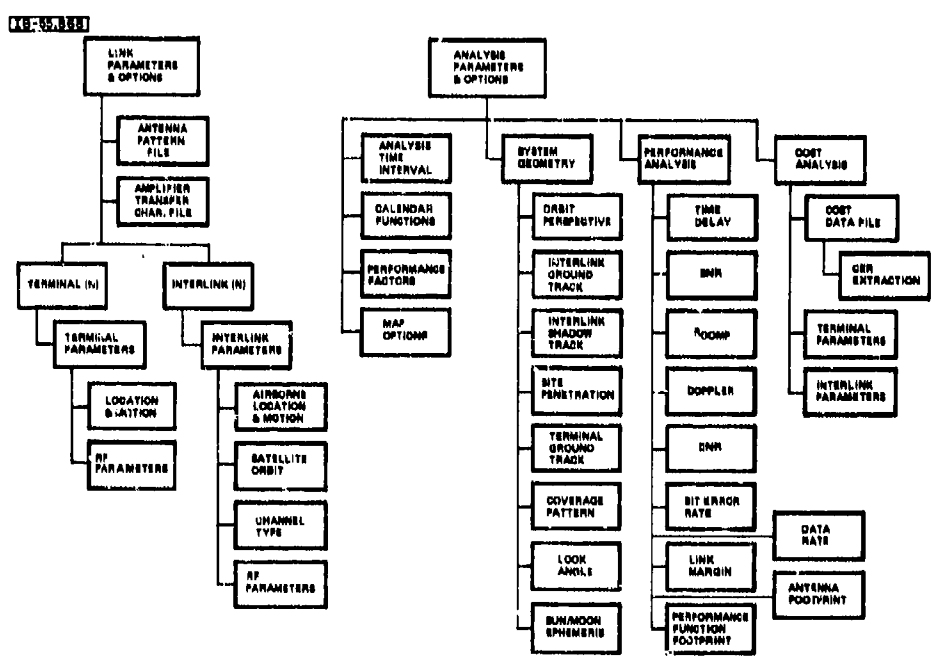

Fig.8 Lower level program control structure (partial)

```
LINK PARAMETERS & OPTIONS

    0 DESELECT
    1 ANTENNA PATTERN FILE              ANTD2RA
    2 AMPLIFIER TRANSFER CHAR FILE     AMPD2A2E
    3 TERMINAL (NUMBER)                       0
    4 INTERLINK (NUMBER)                      0
    5 COST LINK (K$)                          0

MAKE SELECTION:
```

Fig.9 Top level link definition menu

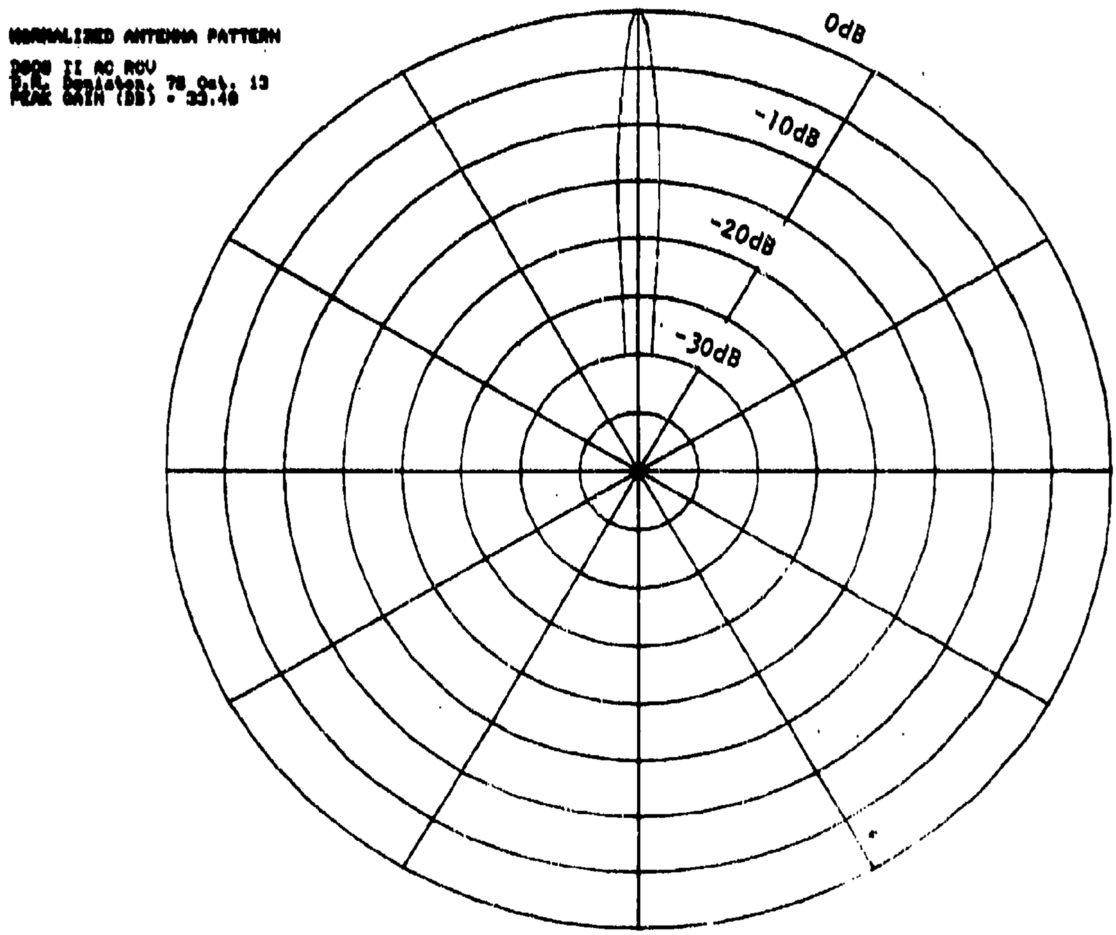

Fig.10 DSCS II area coverage receive antenna pattern

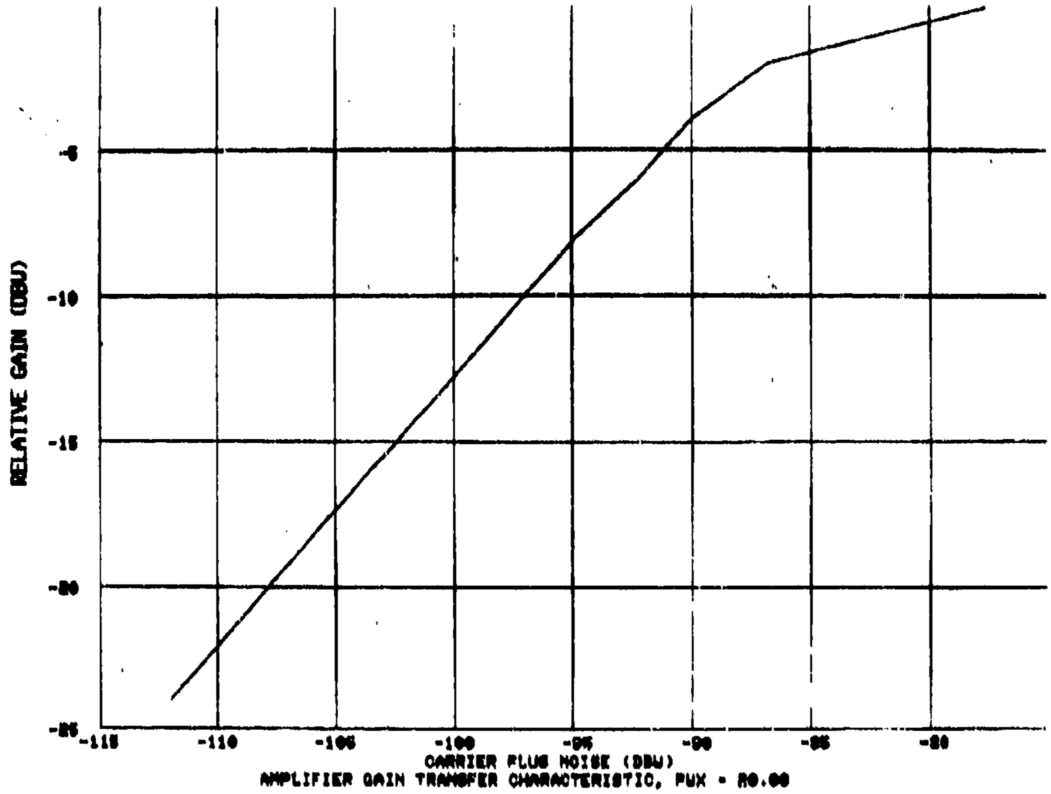

Fig.11 DSCS II Channel 2 transponder characteristic

```
TERMINAL PARAMETERS

     0 NO CHANGE
     1 NAME                               TSC-94
     2 ENABLEMENT INDICATOR                    1
     3 FIXED/MOBILE OPTION                     0
     4 RF PARAMETERS & OPTIONS
     5 COST                                  303

MAKE ANY CHANGE:
```

Fig.12 Terminal definition menu

```
TERMINAL LOCATION & MOTION PARAMETERS

    0 NO CHANGE
    1 LOCATION                        LANDSTUHL
    2 GEODETIC LATITUDE (DEG)            49.40
    3 EAST LONGITUDE (DEG)                7.53
    4 ALTITUDE (M)                         570
    5 GROUND SPEED (M/SEC)                   0
    6 HEADING (DEG)                       0.00
    7 EPOCH (U.T.) (JD HRS MIN SEC)          0   0   0   0.0

MAKE ANY CHANGE:
```

Fig.13 Terminal location/motion definition menu

```
TERMINAL RF OPTIONS & PARAMETERS

     0 NO CHANGE
     1 TRANSMIT POWER (KW)                   0.500
     2 NON-LINEAR OPT & BACKOFF (DB)         0          0.0
     3 TRANSMIT FREQUENCY (MHZ)              8125
     4 XMT DOPPLER TRACK OPTION              0
     5 TRANSMIT BANDWIDTH (KHZ)              1152.0
     6 XMT ANT PNT OPT, ZD, AZ (DEG)         0          0.00        0.00
     7 XMT PAT SEL (=1/P,=2/S,=3/T)          1
     8 XMT ANT DIA, EFF, ROUGH               2.4        0.5         0.0
     9 XMT FEED LOSS (DB)                    -0.5
    10 XMT MODULATION CLASS SELECT           2
    11 XMT MODULATION TYPE SELECT            1
    12 XMT MODULATION ORDER SELECT           4

    13 DIPLEXER OPTION                       0

    14 RCV FREQUENCY (MHZ)                   7400
    15 RCV DOPPLER TRACK OPTION              0
    16 RECEIVE BANDWIDTH (KHZ)               1152.0
    17 RCV ANT PNT OPT, ZD, AZ (DEG)         0          0.00        0.00
    18 RCV PAT SEL (=1/P,=2/S,=3/T)          1
    19 RCV ANT DIA, EFF, ROUGH               2.4        0.5         0.0
    20 RCV ANTENNA NOISE TEMP (DEG K         90.0
    21 RECEIVE FEED LOSS (DB)                -2.0
    22 RCV AMPLIFIER GAIN (DB)               26.0
    23 RCV AMP NOISE TEMP (DEG K)            120.0
    24 RECEIVE LINE LOSS (DB)                -0.2
    25 RECEIVER NOISE TEMP (DEG K)           1500.0
    26 RCV MODULATION CLASS  SELECT          2
    27 RCV MODULATION TYPE SELECT            1
    28 RCV MODULATION ORDER SELECT           4
    29 SYSTEM RECEIVE TEMP (DEG K)           300.0

MAKE ANY CHANGE:
```

Fig.14 Terminal RF parameter definition menu (TSC-94)

```
INTERLINK OPTIONS & PARAMETERS

     0 NO CHANGE
     1 NAME                                 DSCS2 AT
     2 ENABLEMENT INDICATOR                        1
     3 AIRBORNE/SPACEBORNE OPTION                  1
     4 CHANNEL TYPE SELECT                         1
       = 1/TRANSPONDER
       = 2/REGENERATOR
       = 3/TRANSPLEXER
     5 XMT AMP OPT, GAIN (DB) & NAME               0       94.9   CH2
     6 RF PARAMETERS & OPTIONS
     7 COST (K$)                                   0

MAKE ANY CHANGE:
```

Fig.15 Interlink definition menu (DSCS II, Channel 2)

```
ORBITAL PARAMETERS

    0 NO CHANGE
    1 MAJOR SEMI-AXIS (KM)                  42240.4
    2 PERIOD (HRS MIN SEC)                       23  59  58.8
    3 ECCENTRICITY                          .00000
    4 INCLINATION (DEG)                       2.00
    5 ARGUMENT OF PERIGEE (DEG)               0.00
    6 LONGITUDE ASCENDING NODE (DEG         345.00
    7 EPOCH U.T. (JD HRS MIN SEC)  2443587   0    0   0.0

MAKE ANY CHANGE:
```

Fig.16 Orbit definition menu (DSCS II, Atlantic)

```
INTERLINK RF OPTIONS & PARAMETERS

    0 NO CHANGE
    1 TRANSMIT POWER (KW)                      0.020
    2 NON-LINEAR OPT & BACKOFF (DB)                0        0.0
    3 TRANSMIT FREQUENCY (MHZ)                  7400
    4 XMT DOPPLER TRACK OPTION                     0
    5 TRANSMIT BANDWIDTH (KHZ)                1152.0
    6 XMT ANT PNT OPT, ZD, AZ (DEG)                0       0.00       0.00
    7 XMT PAT SEL (=1/P,=2/S,=3/T)                 3    ANTD2XE
    8 XMT ANT DIA, EFF, ROUGH                    0.1        1.0        0.0
    9 XMT FEED LOSS (DB)                         0.0
   10 XMT MODULATION CLASS SELECT                  2
   11 XMT MODULATION TYPE SELECT                   1
   12 XMT MODULATION ORDER SELECT                  4

   13 DIPLEXER OPTION                              0

   14 RCV FREQUENCY (MHZ)                       8125
   15 RCV DOPPLER TRACK OPTION                     0
   16 RECEIVE BANDWIDTH (KHZ)                50000.0
   17 RCV ANT PNT OPT, ZD, AZ (DEG)                0       7.20      28.00
   18 RCV PAT SEL (=1/P,=2/S,=3/T)                 3    ANTD2RA
   19 RCV ANT DIA, EFF, ROUGH                    0.1        1.0        0.0
   20 RCV ANTENNA NOISE TEMP (DEG K              0.0
   21 RECEIVE FEED LOSS (DB)                     0.0
   22 RCV AMPLIFIER GAIN (DB)                    0.0
   23 RCV AMP NOISE TEMP (DEG K)              1000.0
   24 RECEIVE LINE LOSS (DB)                     0.0
   25 RECEIVER NOISE TEMP (DEG K)                0.0
   26 RCV MODULATION CLASS  SELECT                 2
   27 RCV MODULATION TYPE SELECT                   1
   28 RCV MODULATION ORDER SELECT                  4
   29 SYSTEM RECEIVE TEMP (DEG K)             5500.0

MAKE ANY CHANGE:
```

Fig.17 Interlink RF parameter definition menu (DSCS II, Channel 2)

```
ANALYSIS PARAMETERS & OPTIONS

    0 DESELECT

    START TIME U.T.
    1 JD HRS MIN SEC                    2443587  0  0  0.0
    STEP TIME
    2 HRS MIN SEC                                0 10  0.0
    STOP TIME U.T.
    3 JD HRS MIN SEC                    2443588  0  0  0.0

    4 CALENDAR FUNCTIONS
    5 PERFORMANCE FACTORS

    6 MAP OPTIONS & PARAMETERS
    7 SYSTEM GEOMETRY
    8 PERFORMANCE ANALYSIS
    9 COST ANALYSIS
   10 COST/PERFORMANCE\ANALYSIS

MAKE SELECTION:
```

Fig.18 Top level analysis control menu

```
MAP ONLY PARAMETERS & OPTIONS

    0 NO CHANGE
    1 MAP COORDINATE SELECT                  2
      - 1/CYLINDRICAL EQUIDISTANT
      - 2/ORTHOGRAPHIC
      - 3/POLAR
    2 MAP SELECT                             1
      - 0/NO MAP
      - 1/WORLD
      - 2/CONUS
    3 MAP GEODETIC LATITUDE (DEG)        20.00
    4 MAP EAST LONGITUDE (DEG)          -50.00
    5 MAP ORIENTATION ANGLE (DEG)        20.00
    6 MAP VIEWING ALTITUDE (KM)       299999.9
    7 MAP RELATIVE SIZE                   1.00
    8 MAP GRID OPTION                        1
    9 MAP GRID LAT RESOLUTION (DEG)      15.00
   10 MAP GRID LON RESOLUTION (DEG)      15.00
   11 MAP TERMINAL SITE CURSOR OPT           1
   12 DISPLAY MAP

MAKE ANY CHANGE:
```

Fig.19 Map selection menu

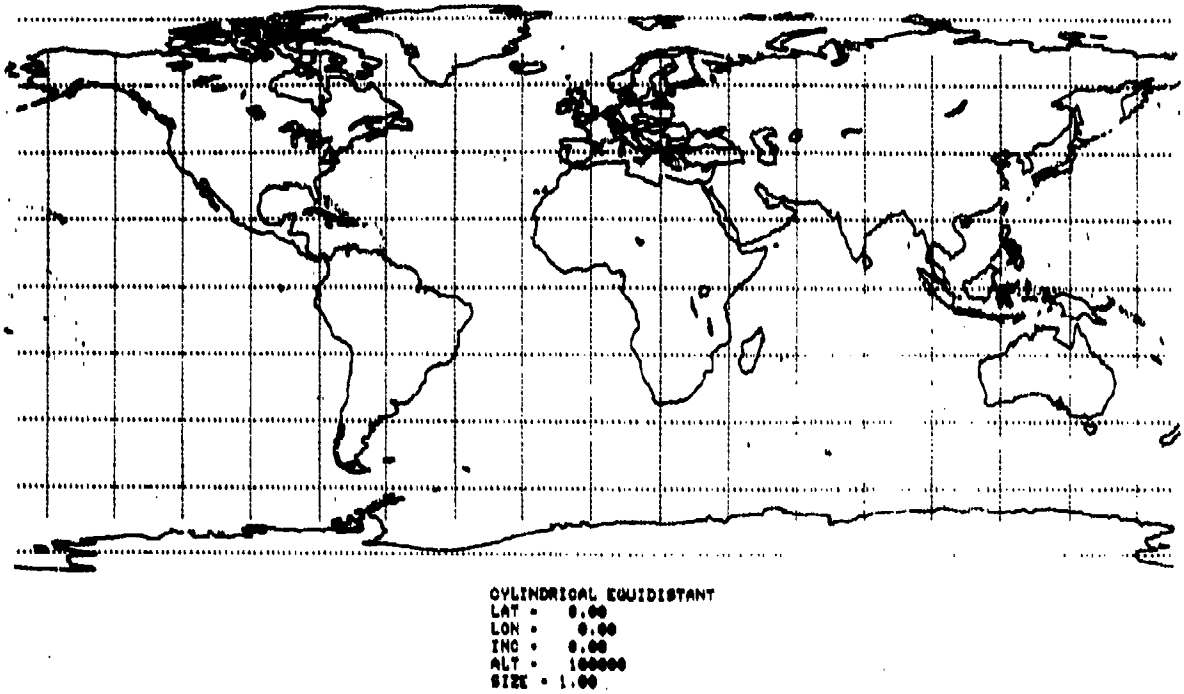

Fig.20 Cylindrical equidistant map projection (as viewed from 100,000 km)

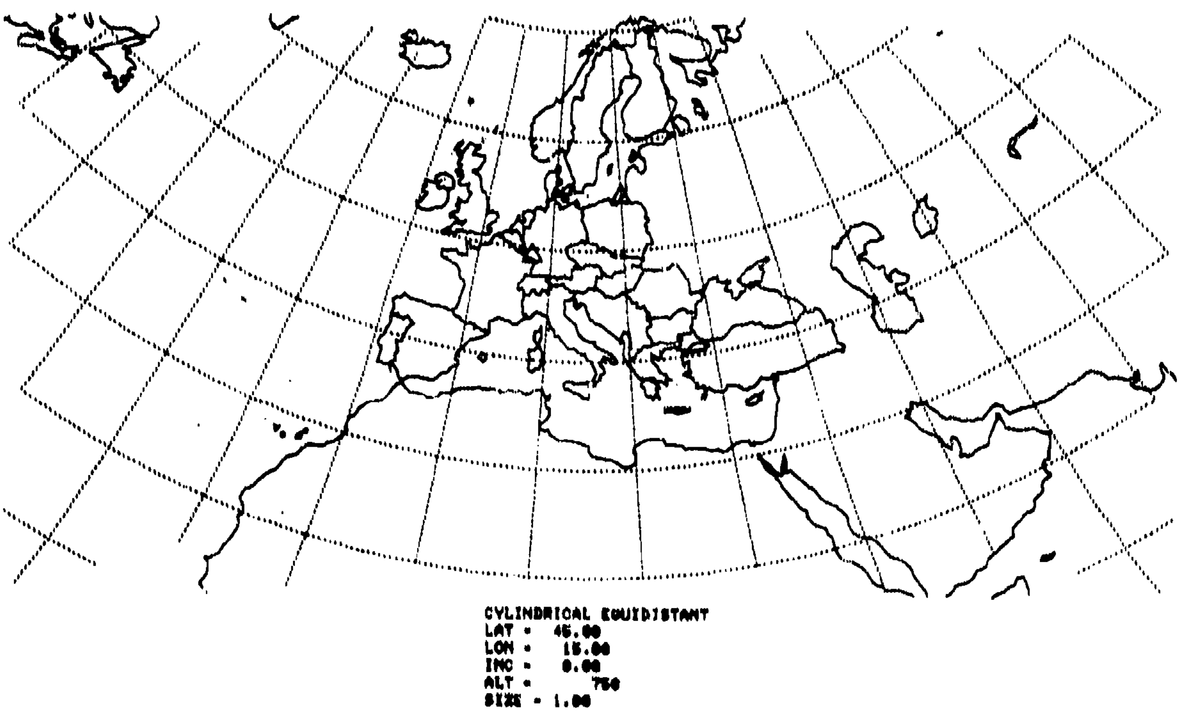

Fig.21 Cylindrical equidistant map projection (as viewed from 750 km)

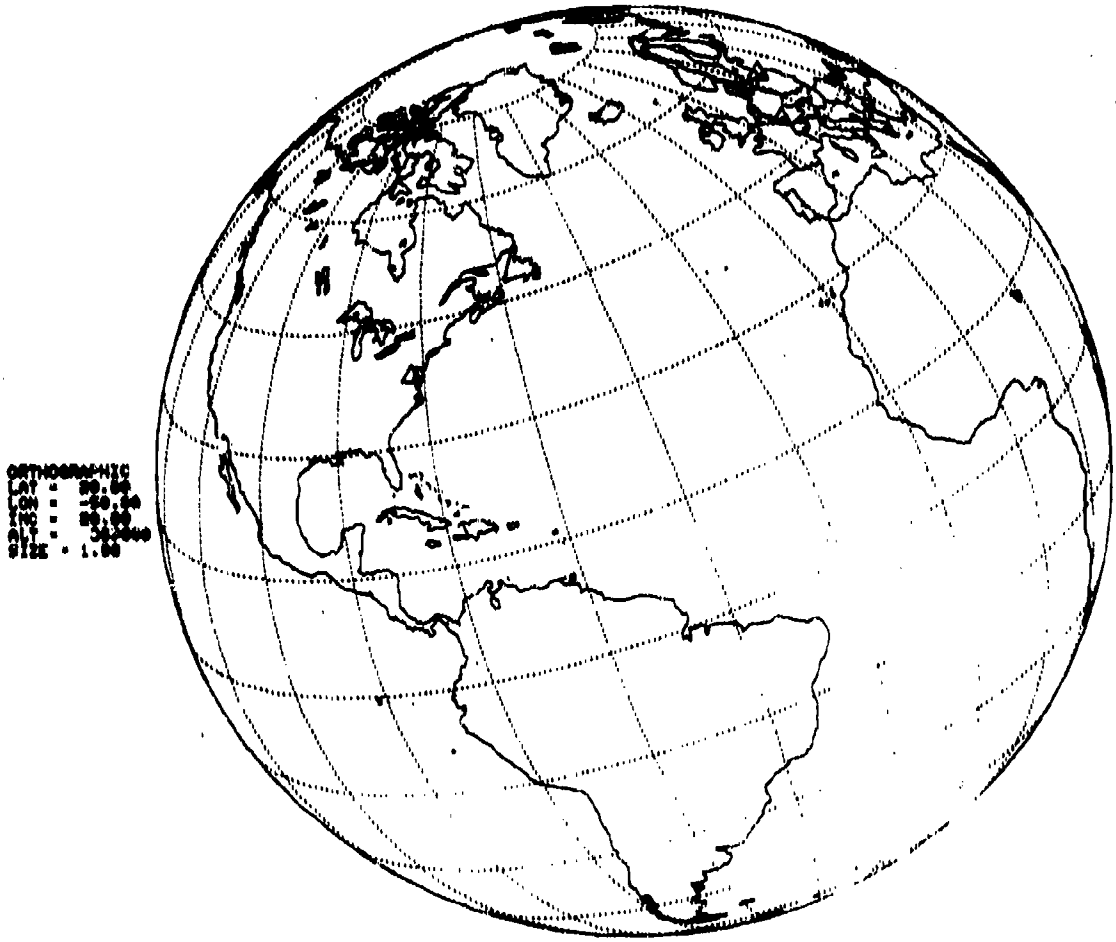

Fig.22 Orthographic map projection (as viewed from 300,000 km)

SYSTEM GEOMETRY PARAMETERS & OPTIONS

0 NO SELECTION
1 ORBIT PERSPECTIVE
2 INTERLINK GROUND TRACK
3 INTERLINK SHADOW GROUND TRACK
4 SITE PENETRATION
5 TERMINAL GROUND TRACK
6 GROUND COVERAGE PATTERN
7 INTERLINK LOOK ANGLE
8 SUN EPHEMERIS
9 MOON EPHEMERIS
10 WORLD VIEW

MAKE SELECTION:

Fig.23 System geometry control menu

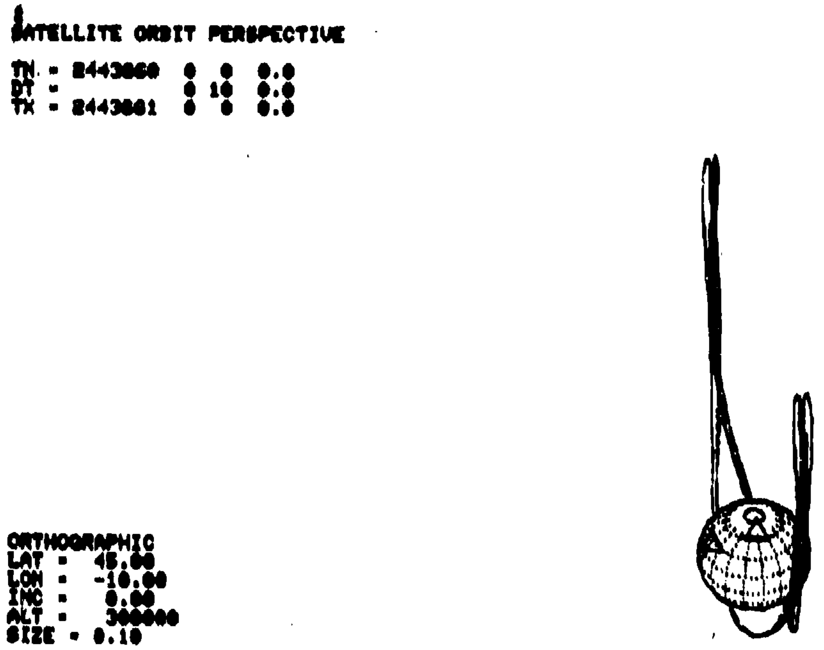

Fig.24 Satellite orbit perspective

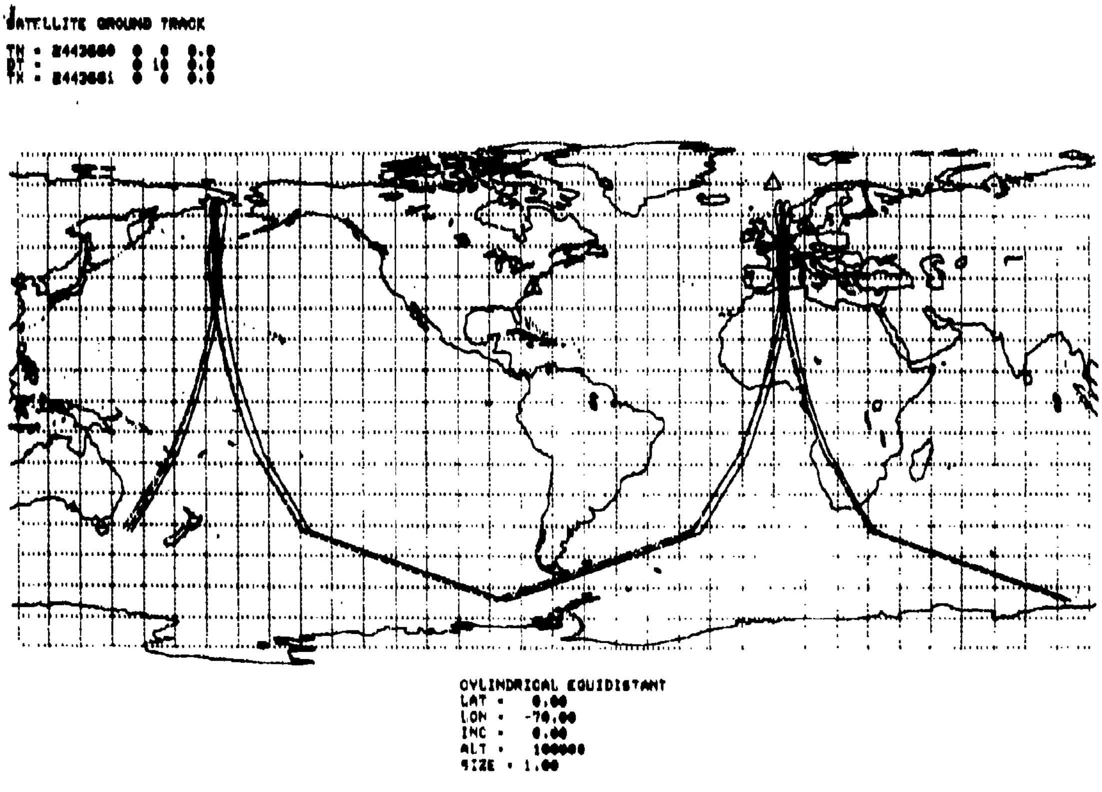

Fig.25 Satellite ground track

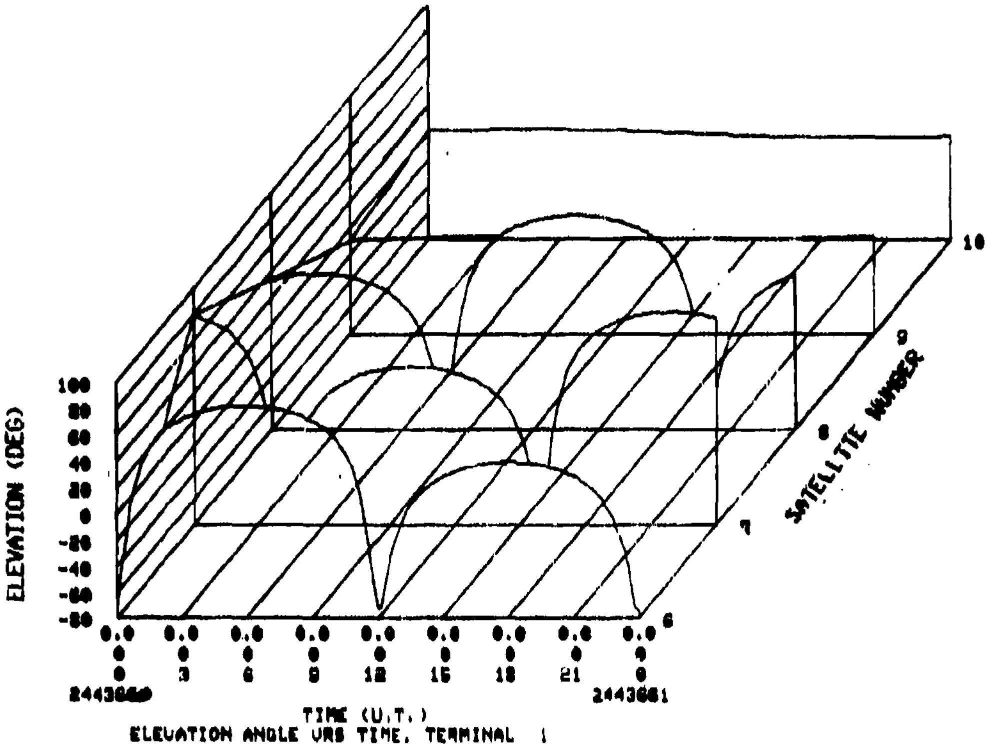

Fig.26 Elevation angle

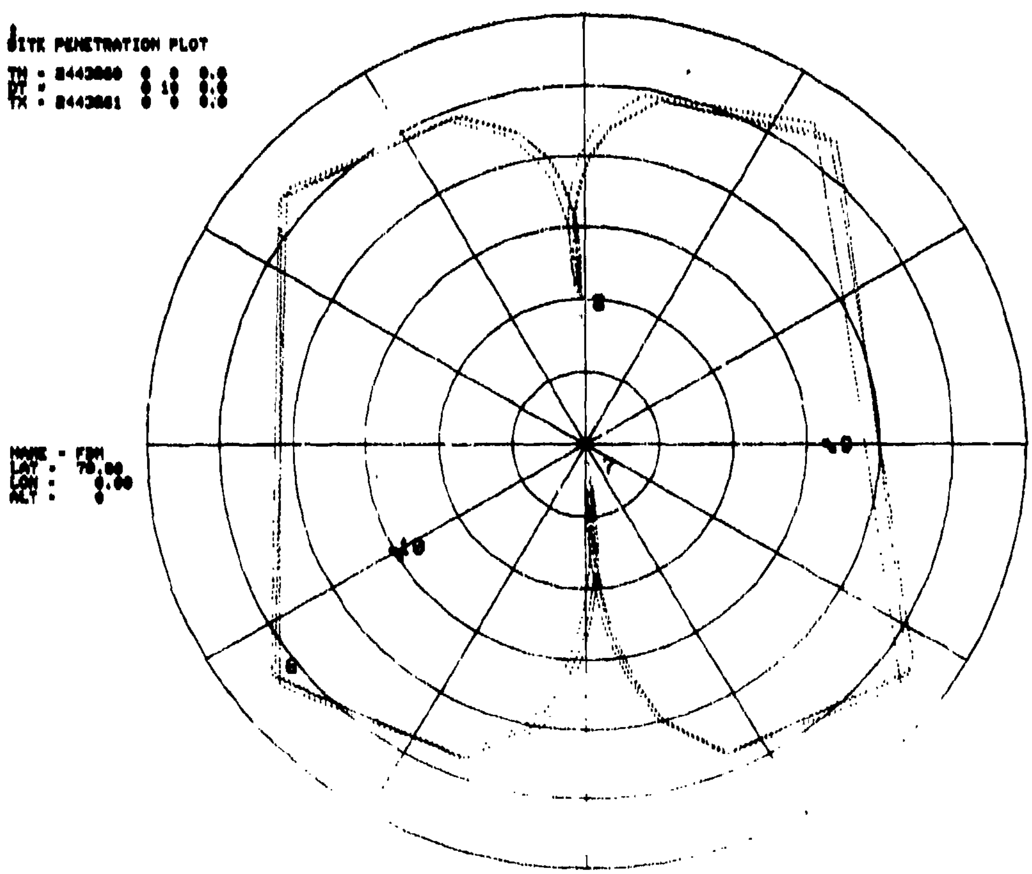

Fig.27 Azimuth and elevation angle

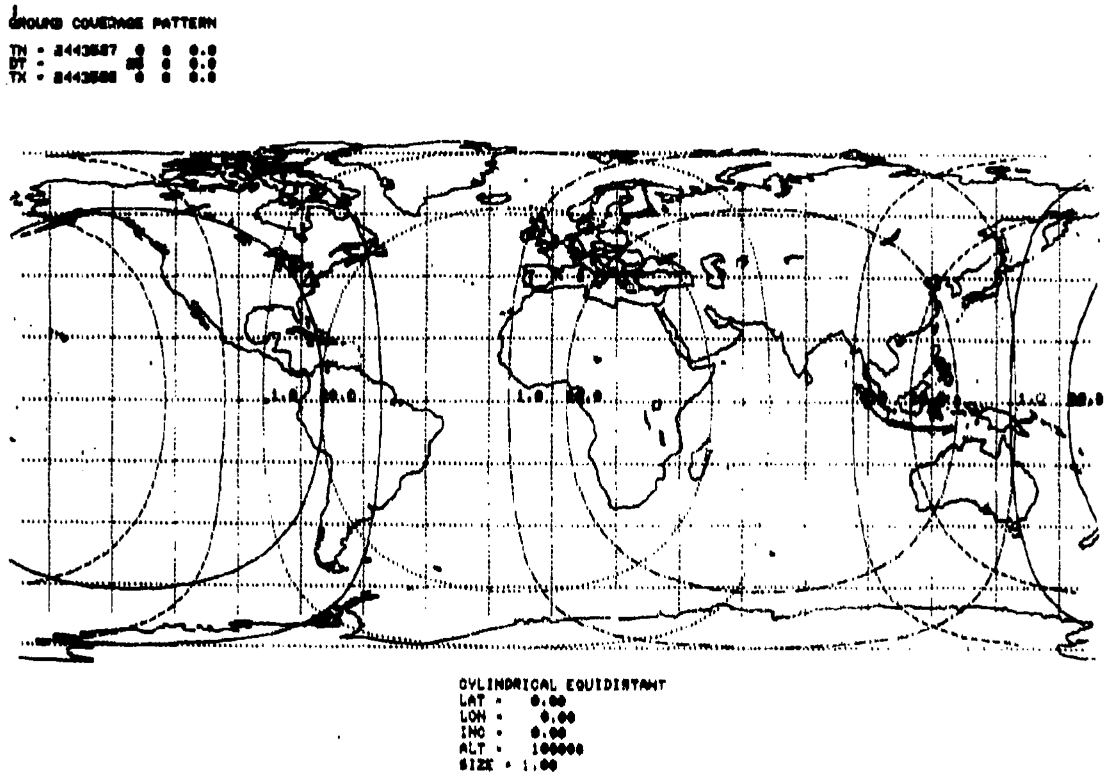

Fig.28 Ground coverage pattern (four DSCS II satellites)

```
PERFORMANCE ANALYSIS PARAMETERS & OPTIONS

    0 NO SELECTION
    1 UPLINK TERMINAL NUMBER                      1
    2 DOWNLINK TERMINAL NUMBER                    3
    3 PERFORMANCE SELECT                          0
      = 1/TIME DELAY
      = 2/SNR
      = 3/RCOMP
      = 4/DRCOMP
      = 5/RCOMP PE
      = 6/DOPPLER
      = 7/ENR
      = 8/PE
      = 9/R
      =10/MARGIN
    4 ANTENNA PATTERN FOOTPRINT
    5 ANTENNA PATTERN SKYPRINT
    6 PER FUNCTION FOOTPRINT

MAKE SELECTION:
```

Fig.29 Performance analysis control menu

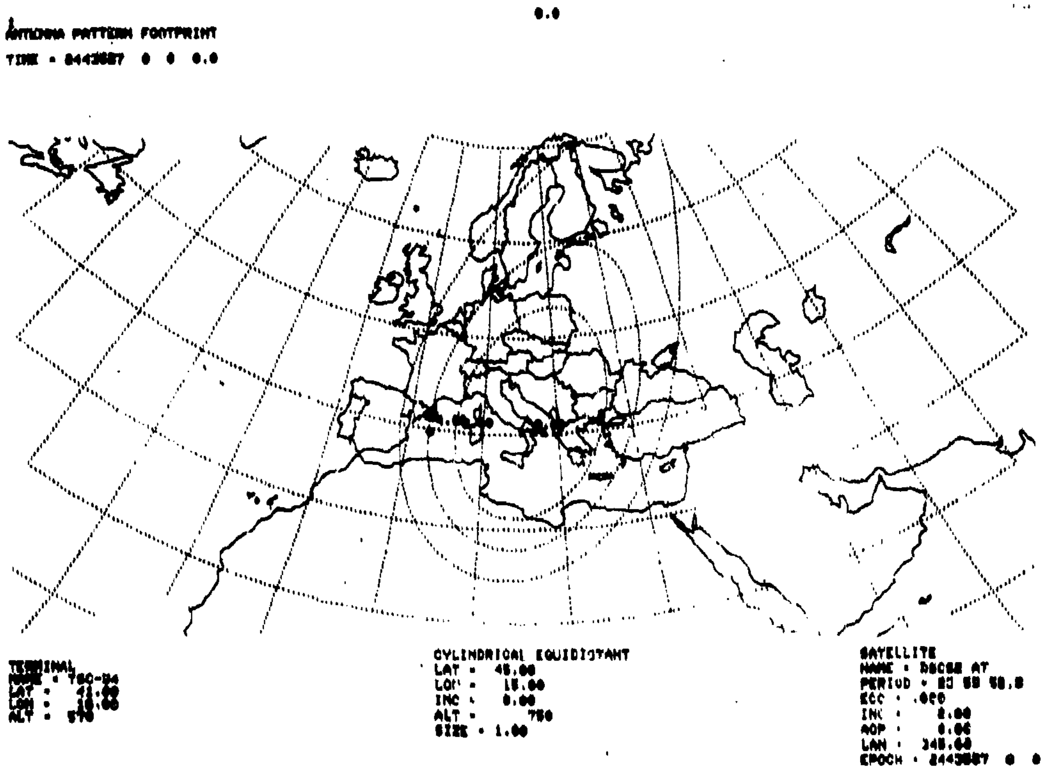

Fig.30 DSCS II area coverage antenna pattern footprint

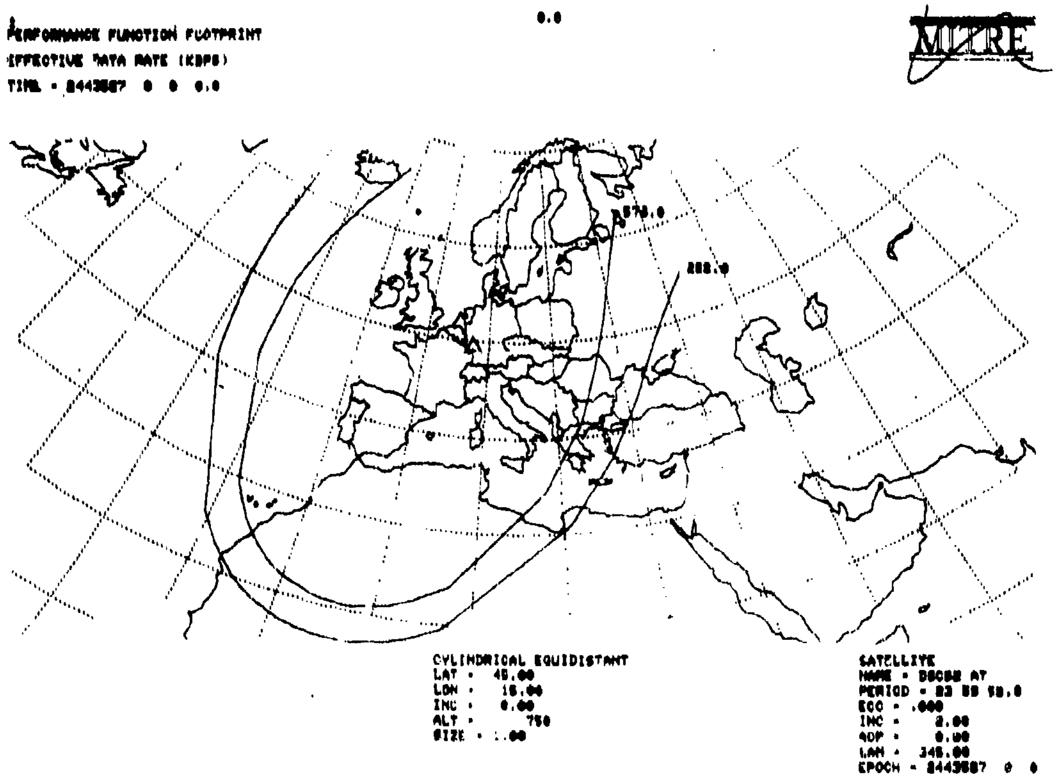

Fig.31 Performance function footprint (data rate)

```
COST ANALYSIS PARAMETERS & OPTIONS

     0 NO SELECTION
     1 COST DATA FILE                        CSTLNAC
     2 TERMINAL PARMS
     3 INTERLINK PARMS
     4 COST LINK

MAKE SELECTION:
```

Fig.32 Cost analysis control menu

```
COST FILE PARAMETERS & DATA

    COMPONENT                          LOW NOISE AMP
    MANUFACTURER                       COMMERCIAL
    IDENTIFICATION                     RUDDY,78
    NUMBER OF VALUES                             40
    NUMBER OF PARAMETERS & NAMES                  3
                                       NOISE TEMP.,K
                                       FREQ.,GHZ
                                       BW,GHZ
    COST & PARAMETER VALUES
```

22.000	42.000	4.000	0.500
24.000	44.000	4.000	0.500
24.000	46.000	4.000	0.500
19.500	50.000	4.000	0.500
19.000	52.000	4.000	0.500
18.500	55.000	4.000	0.500
17.500	66.000	4.000	0.500
12.500	84.000	4.000	0.500
12.000	85.000	4.000	0.500
11.000	95.000	4.000	0.500
2.500	120.000	4.000	0.500
65.000	16.000	4.000	0.500
20.000	40.000	4.000	0.500
17.000	60.000	4.000	0.500
4.000	90.000	4.000	0.500
85.000	35.000	11.000	0.500
26.000	115.000	11.000	0.500
95.000	43.000	15.000	0.100
50.000	235.000	20.000	2.000
27.000	30.000	4.000	0.500
19.000	55.000	4.000	0.500
14.000	70.000	4.000	0.500
10.000	90.000	4.000	0.500
12.000	120.000	12.000	0.500
13.000	180.000	12.000	0.250
90.000	30.000	12.000	0.500
75.000	40.000	12.000	0.500
65.000	60.000	12.000	0.500
20.000	150.000	12.000	0.500
11.000	250.000	12.000	0.500
5.000	400.000	12.000	0.500
23.000	20.000	2.000	0.200
20.000	40.000	2.000	0.200
15.000	80.000	2.000	0.200
10.000	[illegible]	2.000	0.200
8.000	100.000	2.000	0.200
3.500	200.000	2.000	0.200
12.000	50.000	0.700	0.100
10.000	80.000	0.700	0.100
3.000	120.000	0.700	0.100

```
CONTINUE:
```

Fig.33 Cost file for low noise amplifiers

EXTRACT CER PARAMETERS & OPTIONS

0 DESELECT
1 CER SELECT 3

$$=1/\ C = A_0 + A_1 * X_1 + A_2 * X_2 + \ldots + A_M * X_M$$

$$=2/\ C = A_0 + A_1 * X_1^{B_1} + A_2 * X_2^{B_2} + \ldots + A_M * X_M^{B_M}$$

$$=3/\ C = A_0 * X_1^{B_1} * X_2^{B_2} \ldots * X_M^{B_M}$$

2 EXTRACT CER

MAKE SELECTION:

Fig.34 CER extraction selection menu

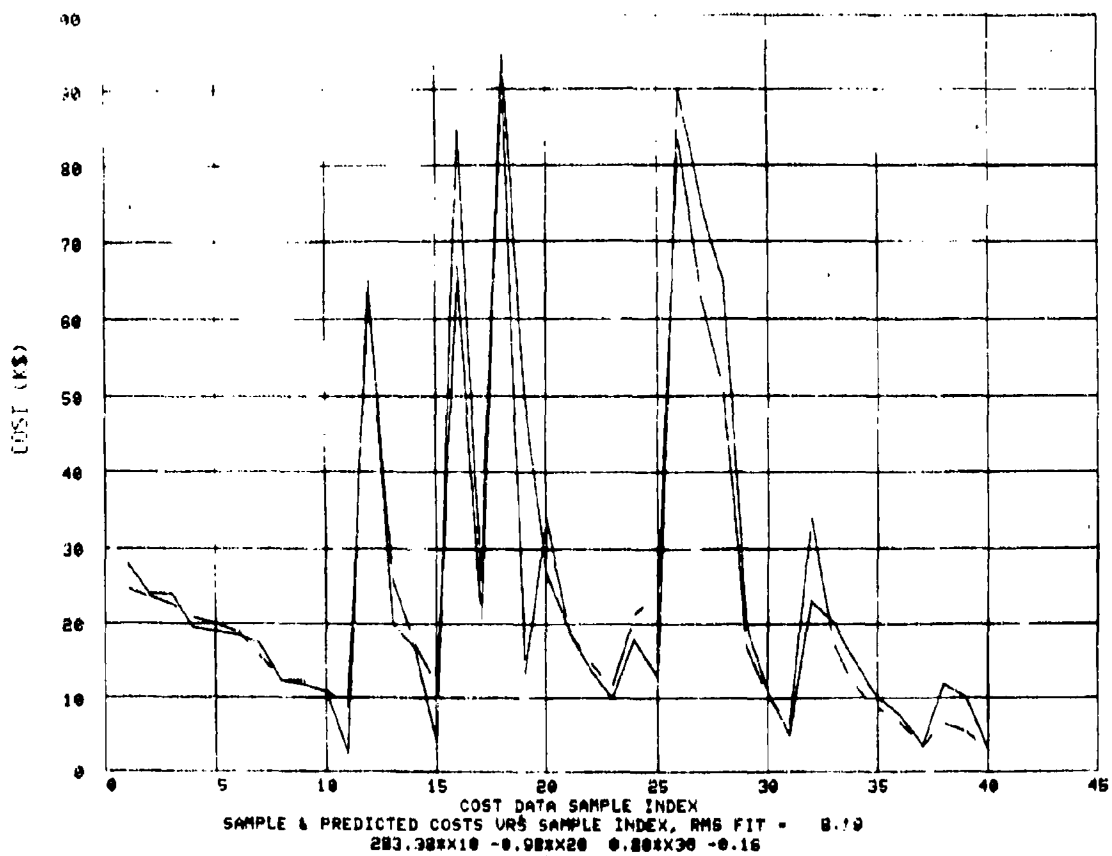

Fig.35 Sample CER and RMS fit to data (low noise amp)

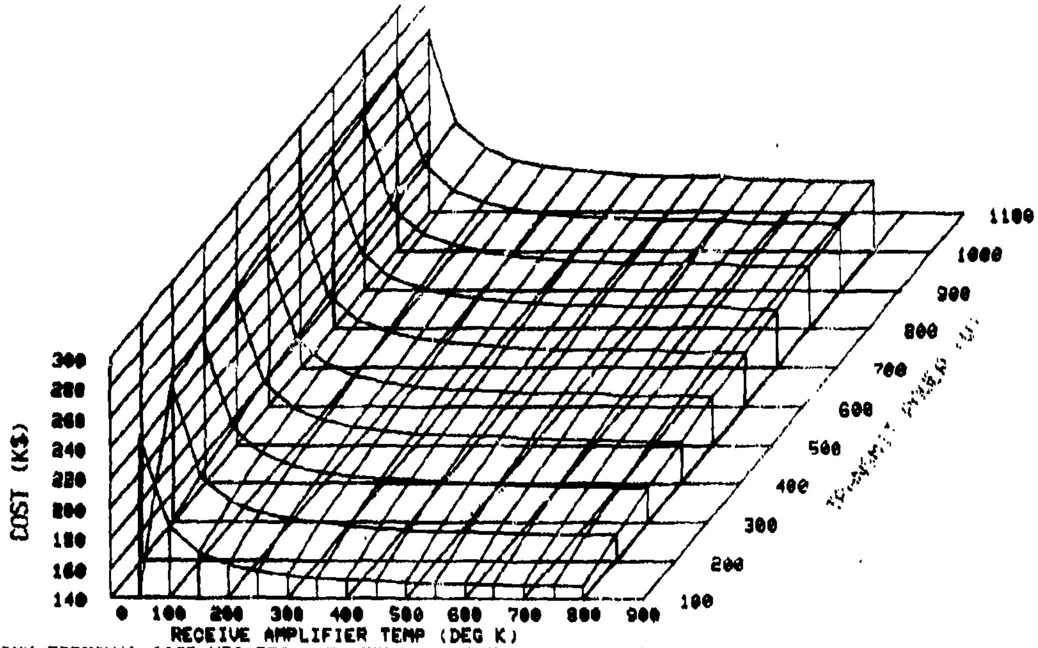

Fig.36 Uplink terminal cost vs RCV amplifier temperature and transmit power

```
TERMINAL RF OPTIONS & PARAMETERS

    0 NO CHANGE
    1 TRANSMIT POWER (KW)                      2.000
    2 NON-LINEAR OPT & BACKOFF (DB)                0         0.0
    3 TRANSMIT FREQUENCY (MHZ)                  8125
    4 XMT DOPPLER TRACK OPTION                     0
    5 TRANSMIT BANDWIDTH (KHZ)                1152.0
    6 XMT ANT PNT OPT, ZD, AZ (DEG)                0        0.00        0.00
    7 XMT PAT SEL (=1/P,=2/S,=3/T)                 1
    8 XMT ANT DIA, EFF, ROUGH                   18.3         0.5         0.0
    9 XMT FEED LOSS (DB)                        -2.0
   10 XMT MODULATION CLASS SELECT                  2
   11 XMT MODULATION TYPE SELECT                   1
   12 XMT MODULATION ORDER SELECT                  4

   13 DIPLEXER OPTION                              0

   14 RCV FREQUENCY (MHZ)                       7400
   15 RCV DOPPLER TRACK OPTION                     0
   16 RECEIVE BANDWIDTH (KHZ)                 1152.0
   17 RCV ANT PNT OPT, ZD, AZ (DEG)                0        0.00        0.00
   18 RCV PAT SEL (=1/P,=2/S,=3/T)                 1
   19 RCV ANT DIA, EFF, ROUGH                   18.3         0.5         0.0
   20 RCV ANTENNA NOISE TEMP (DEG K             90.0
   21 RECEIVE FEED LOSS (DB)                    -2.0
   22 RCV AMPLIFIER GAIN (DB)                   26.0
   23 RCV AMP NOISE TEMP (DEG K)               120.0
   24 RECEIVE LINE LOSS (DB)                    -0.2
   25 RECEIVER NOISE TEMP (DEG K)             1500.0
   26 RCV MODULATION CLASS  SELECT                 2
   27 RCV MODULATION TYPE SELECT                   1
   28 RCV MODULATION ORDER SELECT                  4
   29 SYSTEM RECEIVE TEMP (DEG K)              132.0

MAKE ANY CHANGE:
```

Fig.37 FSC-78 terminal RF parameters

NOUVELLES POSSIBILITES OFFERTES PAR UN SYSTEME DE GUIDAGE HYBRIDE RADIO - INERTIEL ETUDIE EN SIMULATION NUMERIQUE

par

D. BUISSON, J. IRVOAS et J. GROSSIN

S. N. I. Aérospatiale

316, route de Bayonne, TOULOUSE, FRANCE

SUMMARY

The study of a radio-inertial guidance system was initiated to increase the accuracy of aircraft guidance along the ILS beams and to ensure continuation of automatic landing in the event of a localizer transmitter failure (reference (1)).

New developments of the study ensure a new function, namely the detection of deviations of the Loc beam centerline after an undetected failure of the monitoring of the Loc axis alignment with the runway axis, in order to achieve Category III decision heights on Category II ILS Beams.

A digital simulation study has allowed us to demonstrate the system performance. It was based upon different items ; firstly aircraft, auto-pilot, inertial navigation system error, Loc beam perturbation modeling was studied. Later, after AIRBUS A.300 flight tests, the simulation results were compared to the flight test results. Many automatic landing simulations have allowed us to know the system possibilities from the probabilistic point of view with good accuracy. Certification of the system for use by the French domestic airline AIR INTER is in progress with the French Authorities.

NOTATIONS

DME	: Distance Measuring Equipment
FMC	: Flight Management Computer
ILS	: Instrument Landing System
INS, ISS	: Inertial Navigation System, Inertial Sensor System
LISS	: Loc Inertial Statistic System
PA	: Pilote Automatique
$\eta_{mes}, \hat{\eta}, \eta_{vrai}$	: Ecart angulaire de l'avion par rapport à l'axe piste mesuré respectivement estimé, vrai
$y_{mes}, \hat{y}, y_{vrai}$	: Ecart métrique de l'avion par rapport à l'axe piste mesuré respectivement estimé, vrai
ε glide	: Signal glide mesuré
h_{RA}	: Altitude radio-altimètre
$V_N, V_{N_I}, \Delta V_N, \gamma_N t$	: Composantes de la vitesse Nord vraie, respectivement indiquée, erreur de vitesse, dérive avec le temps
$V_E, V_{E_I}, \Delta V_E, \gamma_E t$	: Composantes de la vitesse Est vraie, respectivement indiquée, erreur de vitesse, dérive avec le temps
$V_T, V_{T_I}, \Delta V_T, \gamma_T t$	: Composantes de la vitesse transversale vraie, respectivement indiquée, erreur de vitesse, dérive avec le temps
R, R_I	: Route, route indiquée par la centrale inertielle
R_f	: Route de référence pour la projection des vitesses inertielles
δR_o	: Ecart angulaire entre l'axe moyen du faisceau Loc et la référence de projection des vitesses Rf
$\Delta\eta$	: Décalage angulaire du faisceau Loc
Ψ_{set}	: Cap géographique de la piste
S_1	: Sensibilité de l'écart Loc (en μA/rd)
D_1 , D_s	: Distance de l'avion par rapport à l'émetteur Loc, au seuil de piste
p_s, r_s, p_1, r_1	: Composantes de la vitesse angulaire de l'avion en roulis et lacet dans les axes de stabilité (indice S) et dans les axes avion (indice 1)
$\beta_{aéro}, \beta_{sol}$	: Dérapage aérodynamique et par rapport au sol
δp , δr	: Braquages des gouvernes de gauchissement et de direction
X , $\hat{X}$	: Vecteur d'état du filtre de Kalman réel, puis estimé

y, u : Vecteur de mesure ($Y = HX + W$), vecteur d'entrée du système

Σ : Matrice de covariance des erreurs d'estimation ($X - \hat{X}$)

1 - INTRODUCTION

L'amélioration du guidage d'un avion en approche finale par l'utilisation de termes inertiels a déjà fait l'objet de nombreuses études afin de réduire les minima de visibilité imposés par la nature des équipements au sol (ILS). C'est à l'instigation de la compagnie aérienne intérieure française AIR INTER qu'une étude a été entreprise en 1975, sous contract des services officiels, par la société AEROSPATIALE en collaboration avec la société SAGEM.
Les objectifs initiaux étaient les suivants :

a) Filtrage des informations LOCALIZER (LOC) afin d'obtenir la réduction des écarts de trajectoire latérale, des mouvements de roulis et lacet et des agitations des gouvernes.

b) Survie du guidage à une panne de l'émetteur LOC à basse altitude, en particulier de 100 ft jusqu'à l'impact sur des installations ILS de categorie II ou III.

Le système mis au point à partir de ces deux objectifs a été présenté à la conférence AGARD/GCP de Stuttgart en mai 1977 (réf (1)) et a été essayé en vol sur l'AIRBUS n° 3 en 1977. Cependant, pour la certification du système avec des minima de catégorie III alors que l'ILS n'est que de catégorie II, les services officiels français ont demandé que le système LOC Inertiel LISS réponde à un 3è objectif pour pallier le manque de surveillance des LOC de catégorie II, à savoir :

c) Détection d'un faisceau LOC en moyenne décalé de l'axe réel de la piste, à la suite d'une panne non détectée du moniteur de surveillance de l'ILS.

Le système présenté ici permet de répondre à cette nouvelle demande sous certaines conditions. La détermination et la validation des performances du système en vue de son acceptation par les services officiels furent fondées en grande partie sur les études en simulation numérique et c'est cet aspect plus particulier que nous allons développer.

2 - PRINCIPE DU SYSTEME LISS

2.1 Principe général

Le système de guidage hybride radio-inertiel LISS est un calculateur qui s'insère entre les récepteurs radio et le pilote automatique. Il fournit au P.A. un signal $\hat{\gamma}$ de même format que le signal LOC brut γ_{mes} qui remplace ce dernier en éliminant au maximum les bruits et distorsions du faisceau LOC. Il reçoit des informations radio et des informations de vitesse issues d'une centrale à inertie :

- γ_{mes} signal LOC brut issu du récepteur ILS en micro-ampères (μA)
- ε_{glide} signal glide brut (ILS) en micro-ampères
- h_{RA} altitude issue du radio-altimètre
- VN_I, VE_I vitesse par rapport au sol projetée selon les axes Nord et Est, indiquée par la centrale à inertie du type INS ou ISS.

Le fonctionnement du filtre LISS est décrit référence (1).
Rappelons qu'il est basé sur le filtre de Kalman-Bucy en profitant du fait que les deux mesures effectuées sont entachées d'erreurs de nature différente (figure 1) :

- Le récepteur LOC délivre un signal proportionnel à l'écart angulaire entre la droite avion-émetteur LOC et l'axe du faisceau. On obtient l'écart métrique par rapport à l'axe faisceau grâce à la connaissance de la distance avion-émetteur D et de la sensibilité du faisceau S_1 :

$$y_{mes} = \gamma_{mes} \times \frac{D}{S1} = y_{vrai} + y_{bruit\ loc} \qquad (1)$$

où $y_{bruit\ loc}$ comprend des bruits radio-électriques et les distorsions du faisceau, dont la moyenne est nulle.

- La centrale à inertie nous fournit, par projection des vitesses Nord et Est sur un axe perpendiculaire à l'axe piste, la dérivée de l'écart latéral, c'est-à-dire la vitesse latérale de l'avion $\dot{y}_I$

$$\dot{y}_I = \dot{y}_{vrai} + e_{VT} \qquad (2)$$

où e_{VT} est l'erreur de vitesse de transversale dûe aux erreurs conjuguées de projection et de la centrale à inertie.

2.2 - Variables d'état estimées

Il s'agit donc de former un filtre du type "filtre complémentaire" entre ces deux informations y_{mes} et $\dot{y}_I$ qui élabore la position vraie de l'avion par rapport à l'axe moyen du faisceau qui doit coïncider avec l'axe piste. Cette position estimée $\hat{y}$ est retransformée en écart angulaire $\hat{\gamma}$ avant d'être dirigée vers le pilote automatique à la place de l'information LOC brute γ_{mes}. L'optimisation du filtre nous a conduit à un filtrage statistique d'ordre 4, c'est-à-dire qui évalue 4 variables d'état :

- $\hat{\gamma}$ l'écart angulaire filtré (en micro-ampères)
- $\hat{\Delta V}_T$ l'erreur constante de vitesse latérale inertielle
- $\hat{\delta}_T$ la dérive avec le temps de l'erreur de vitesse latérale
- $\hat{\delta}_{Ro}$ l'angle d'erreur de projection des vitesses, c'est-à-dire la différence entre la référence de projection et l'axe moyen du faisceau LOC.

Ces variables découlent du modèle des erreurs de vitesse de la centrale à inertie qui sera explicité plus tard (cf chap. 6).

2.3 - Evaluation de la distance

Il faut connaître par ailleurs la distance entre l'avion et l'émetteur LOC pour faire la transformation entre les écarts angulaires η_{mes} (ou $\hat{\eta}$) et des écarts métriques y_{mes} (ou $\hat{y}$).

Pour cela, un filtre complémentaire entre une information de "distance radio" et la vitesse longitudinale de l'avion donnée par la centrale à inertie élabore une distance hybride $\hat{D}$. La "distance radio" est calculée à partir de l'altitude mesurée par le radio-altimètre, du signal glide et des valeurs moyennes de la sensibilité glide Sg, de la pente glide γ_g et de la distance entre l'émetteur LOC et l'émetteur glide le long de l'axe piste soit dgl.
La formule de calcul est la suivante :

$$D_{mes} = \frac{h_{RA}}{\gamma_g + S_g \cdot \varepsilon_{glide}} + d_{gl} \qquad (3)$$

Cette distance pourrait être éventuellement remplacée par une distance provenant d'une autre source, par exemple la distance donnée par un DME implantée à l'émetteur LOC ou encore la distance calculée par un système de navigation de zone inclus dans un système de gestion de vol (FMC).

2.4 - Modes d'initialisation et de reconfiguration

- L'initialisation du filtrage de la distance a lieu quand l'avion est rentré dans la portion d'espace où le signal glide est linéaire, c'est-à-dire au passe en mode "maintien de glide". Quand l'avion est en palier avant la capture du faisceau glide, la distance estimée est la "distance radio" filtrée simplement par un passe-bas.

- L'initialisation du filtrage de l'écart latéral $\hat{\eta}$ a lieu quand l'avion est stabilisé sur l'axe LOC, c'est-à-dire au passage en mode "maintien de LOC".

- En cas de panne momentanée de l'ILS ou de la radio-sonde, le passage au guidage à l'aide des seules informations inertielles recalées des erreurs déjà estimées, a lieu. En dessous de 100 ft et en cas de panne ILS, le système doit être capable d'assurer le guidage de l'avion jusqu'à l'impact et, si possible, au delà.

- Le système détecte également les anomalies LOC d'amplitude significative. En comparant la différence du signal LOC brut η_{mes} et du signal filtré $\hat{\eta}$ à un seuil assez important pour que l'on soit sûr que le signal LOC soit erroné, on passe également au guidage inertiel en attendant que l'anomalie disparaisse. Si l'anomalie LOC dure trop longtemps, le système se déclare incompétent et le signal LOC est transmis au P.A. Le temps de survie est d'ailleurs fonction du degré de recalage des estimations, c'est-à-dire du temps effectif de filtrage.

- En cas de panne de la centrale à inertie, ou encore en cas de panne auto-détectée du calculateur LISS, le système devient "transparent", c'est-à-dire qu'il transmet directement le signal LOC brut à l'entrée du pilote automatique.

2.5 - Principe de la simulation numérique

Ce système a été mis au point à l'aide d'une simulation numérique de l'ensemble de la boucle (cf figure 2) composée des différents sous-ensembles :

- l'avion simulé par les équations linéarisées du mouvement latéral,
- le pilote automatique, dans le mode atterrissage, c'est-à-dire les phases maintien de LOC, pui décrabe à partir de 30 ft jusqu'à l'impact sur la piste,
- les différents détecteurs placés à bord de l'avion fournissant les données nécessaires au P.A., c'est-à-dire le récepteur ILS, la centrale à inertie (partie cap et verticale et partie inertielle) et la radio-sonde.

Des entrées extérieures à cette boucle viennent perturber son fonctionnement. Ce sont successivement :

- le vent latéral et les turbulences atmosphériques,
- les bruits recueillis sur le récepteur ILS (signal glide pour le calcul de la distance et surtout signal LOC),
- le modèle d'erreur de la radio-sonde principalement dû au profil du terrain survolé par l'avion,
- le modèle d'erreurs de la centrale à inertie, en particulier les erreurs de vitesse horizontale par l'intermédiaire de ses deux composantes selon les axes Nord et Est,
- les caractéristiques géométriques de la piste et des implantations des émetteurs ILS.

Nous allons examiner successivement dans les chapitres suivants chacune de ces entrées en détaillant la méthode utilisée pour la modéliser.

La simulation numérique a été effectuée à l'aide des moyens informatiques de l'Aérospatiale à Toulouse, à savoir un ordinateur CYBER 172 couplé à un ordinateur CDC 6600 (cf réf 3).

3 - RECHERCHE D'UN MODELE DE VENTS ET DE TURBULENCES ATMOSPHERIQUES

3.1 - Généralités

Ce chapitre ne fait pas explicitement référence à l'étude Loc-Inertiel puisque, du fait que nous nous sommes imposés de ne pas modifier le Pilote Automatique, le comportement de la boucle de guidage de l'avion vis-à-vis des perturbations atmosphériques n'a pas été changé. Cependant, pour répondre à un marché d'études accordé par le Service Technique de l'Aéronautique français (cf référence (2)), une étude a été effectuée à l'Aérospatiale pour rechercher un modèle des perturbations atmosphériques qui soit assez proche de la réalité.

3.2 - Analyse statistique des vents rencontrés

Une analyse statistique de 152 approches de l'avion "CONCORDE" à Toulouse et à Brétigny (France) a été effectuée. A partir des enregistrements en vol et des mesures de trajectoire, les vents auxquels l'avion a été soumis ont été reconstitués et analysés. Ce sont essentiellement les vents verticaux W_z et longitudinaux W_x.

3.2.1 - Vent vertical

Pour étudier le vent vertical W_z, différents calculs sur les échantillons retenus ont été faits :

- soustraction de la moyenne non représentative d'un phénomène réel,
- calcul de l'écart-type de la turbulence verticale,
- calcul de la fonction d'auto-corrélation, puis comparaison avec la fonction d'auto-corrélation d'un bruit blanc filtré par un filtre passe-pas du 1er ordre. En effet, il est apparu que l'étude des fonctions d'auto-corrélation des échantillons de vents mesurés était plus précise que celles des spectres :

le fait que les enregistrements soient limités (de 30 à 60 secondes) entraîne des erreurs importantes dans le calcul du spectre, alors que ces erreurs sont plus faibles sur la fonction d'auto-corrélation.

3.2.2 - Vent horizontal

L'étude des vents horizontaux a fait apparaître un problème particulier, celui des vents moyens et des gradients de vent. La figure 3a donne le vent W_x calculé au cours d'une approche.

Nous constatons qu'il existe une composante moyenne non constante. Pour comparer les turbulences réelles avec les turbulences décrites dans les divers modèles officiels, il convient donc d'isoler cette composante moyenne pour ne garder que les fréquences plus importantes. Ceci nous permettra de plus, de comparer les composantes moyennes aux gradients de vent proposés par les différents modèles.

Dans ce but, il a fallu trouver une méthode qui permette de ne garder que les hautes fréquences des enregistrements, sans pour autant déphaser ou affaiblir les fréquences voisines de la fréquence de coupure, car sinon les calculs sont faussés.

Pour cela, plutôt que d'utiliser un filtrage temporel classique, un filtrage par la méthode de la transformée de Fourrier a été appliqué. Il permet de faire un filtrage idéal : seules les fréquences désirées sont conservées, sans aucun affaiblissement. La figure 3b présente les résultats du filtrage pour le vent tracé figure 3a : d'un côté la composante moyenne, de l'autre la turbulence horizontale.

La méthode déjà utilisée pour le vent vertical peut alors être appliquée à la turbulence horizontale calcul de l'écart type, de la fonction d'auto-corrélation et enfin de la constante de temps du filtre du bruit coloré qui approche le mieux l'enregistrement étudié.

3.3 - Comparaison avec les modèles officiels -

Les résultats de l'analyse statistique des vents ont été comparés aux modèles proposés par les services officiels américains (F.A.A. ; circulaire AC-20-57 A) et anglais (C.A.A. ; modèle de la norme T.S.S. 1.2).

La figure 4 donne la corrélation qui existe entre, d'une part, les écarts type du vent vertical et de la turbulence horizontale et, d'autre part, le vent moyen à une hauteur de 33 ft, comparée à celle des modèles officiels.

Nous en déduisons les points suivants :

- Les écarts-types des turbulences verticales et horizontales sont pratiquement indépendants du vent moyen lorsque celui-ci est inférieur à 15 kts. Ils sont environ de 1,5 kts pour W_x et pour W_z Ils n'augmentent que lorsque le vent moyen dépasse 15 kts. Une combinaison des modèles FAA et CAA permet de représenter le phénomène.
- L'énergie du vent vertical est concentrée vers les basses fréquences, la période de coupure est de 6,5 sec en moyenne.
- La répartition du spectre des turbulences horizontales correspond à celles des modèles FAA ou CAA.
- La composante moyenne du vent horizontal qu'il faut ajouter aux turbulences horizontales présente une évolution avec l'altitude, mais surtout elle présente des discontinuités qui ne peuvent être générées que par un processus particulier. Ce processus, du type de Poisson, est caractérisé par des sauts à des instants aléatoires obéissant à une loi de Rayleight, l'amplitude des rafales étant aléatoire, répartie suivant une loi gaussienne.

3.4 - Modèle utilisé dans les simulations Loc-Inertiel

Nous avons considéré deux cas différents de vent latéral pour les simulations du guidage hybride radio-inertiel.

- Un vent moyen dont la seule composante est perpendiculaire à la piste et vaut 10 kts.
- Un vent fort, dont le module vaut 25 kts, dirigé de telle sorte qu'il se décompose en un vent de face de 20 kts et un vent latéral de 15 kts. C'est le vent maximum certifié pour effectuer un atterrissage automatique.

A chacun de ces vents constants, nous avons associé les turbulences telles qu'elles sont définies dans la circulaire FAA AC-20-57 A. Leur spectre obéit donc à la loi :

$$\phi(\omega) = \frac{2\sigma^2}{\pi} \frac{T}{1 + T^2\omega^2} \qquad (4)$$

avec $\sigma = 0{,}15\, V_y$ où V_y est la composante moyenne du vent traversier, et $T = \frac{L}{V_o}$ où $L = 600$ ft et V_o est la vitesse aérodynamique de l'avion.

4 - RECHERCHE D'UN MODELE DES BRUITS RECUEILLIS SUR LE RECEPTEUR ILS

4.1 - Modèles existants

L'annexe 10 de la réglementation OACI (Organisation de l'Aviation Civile International) donne les spécifications des installations ILS. Nous sommes surtout concernés par le modèle du faisceau LOC pour l'étude du guidage hybride Loc-Inertiel. La figure 5 présente les valeurs à ne pas dépasser avec une probabilité supérieure à 5 % en ce qui concerne les coudes d'alignement des faisceaux LOC. Toutefois, le document OACI ne précise pas le spectre des bruits. Rappelons que ce qui nous intéresse ici est le bruit global comprenant les distorsions spatiales ou temporelles du faisceau, mais aussi les bruits radio électriques recueillis par l'antenne LOC et les bruits propres du récepteur. Le signal à analyser est donc la différence entre la sortie du récepteur LOC et le signal correspondant à la position latérale de l'avion par rapport à l'axe de la piste.

4.2 - Analyse de quelques faisceaux LOC

Nous présentons un exemple de bruit Loc reconstitué à partir des calculs de trajectoire figure 6. L'enregistrement a été séparé en deux échantillons afin d'étudier l'influence de la distance sur les caractéristiques du bruit LOC. Nous donnons ensuite les calculs de moyenne écart-type et fonction d'autocorrélation (figure 6), pour ce même faisceau. Du fait qu'il existe une très basse fréquence dans le bruit étudié, les moyennes des deux échantillons sont différentes.

Nous avons ensuite, comme pour le modèle de vents proposé au chap. 3, cherché à trouver le filtre passe bas du 1er ordre qui, ayant à son entrée un bruit blanc, possède une sortie dont les caractéristiques sont aussi proches que possible des caractéristiques réelles. Pour cela, il faut identifier la fonction d'auto-corrélation avec :

$$R\,(t) = (\,\sigma^2 + m^2)\,.\,e^{-\frac{|t|}{\tau}} \qquad (5)$$

où τ est la constante du temps du filtre cherché.

4.3 - Modèle de bruits de faisceau LOC

L'étude d'un total de 12 faisceaux LOC (deux faisceaux français fournis par le Service Technique de la Navigation Aérienne français (STNA) et dix faisceaux américains issus du rapport réf (4)), nous a conduit aux conclusions suivantes :

- Ces faisceaux, d'une génération ancienne, ne répondent pas aux spécifications des catégories II ou III, leur écart type étant trop important (6,15 μA au lieu de 2,5 μA). Ils donnent cependant une bonne idée de la structure des faisceaux LOC.

- A mesure que l'on s'éloigne du seuil de la piste, la constante de temps du filtre passe-bas tel que les fonctions d'auto-corrélation soient proches, augmente, c'est-à-dire que les hautes fréquences du bruit sont plus importantes à distance faible de l'émetteur LOC plutôt qu'à distance élevée. Du fait que les écarts-type des bruits sont pratiquement équivalents pour d'une part les échantillons loin de la piste et d'autre part les échantillons près de la piste, les valeurs du spectre du bruit LOC pour les basses fréquences sont plus importantes à distance élevée.

Le modèle de bruits LOC mis au point (figure 7) tient compte de ces remarques. Il sera généré par un bruit blanc passant au travers d'un filtre passe-bas dont la constante de temps diminue quand la distance au seuil de piste diminue, puis multiplié par un gain variable avec la distance et filtré enfin par un passe-bas de 0,5 sec de constante de temps. En final, le niveau du bruit blanc est réglé pour que l'écart type du bruit LOC soit de 2,5 μA au seuil de piste, de telle sorte que les valeurs OACI soient respectées.

En général, dans les simulations d'atterrissage automatique, on utilise un bruit dont le spectre est donné par l'équation (4)

$$\text{avec} \quad \sigma = 2{,}5 \ \mu A \qquad \text{et} \qquad T = 0{,}5 \text{ sec}$$

Le nouveau modèle définit des bruits où les hautes fréquences ont moins d'importance. Le niveau du spectre dans la bande de fréquence de la résonnance de la boucle de guidage de l'avion (périodes $T \simeq 30$ sec) est donc relevé.

On n'atteint cependant pas les valeurs maximum spécifiées par l'OACI pour les distances élevées. Nous avons malgré tout, dans l'étude des réponses du filtre Loc-Inertiel aux différentes courbures de faisceaux, utilisé des distorsions à la limite de la courbe OACI. Mais de telles courbures n'ont pas servi pour les comparaisons statistiques.

4.4 - Modèle de bruits de faisceau glide

Nous avons utilisé le signal glide pour reconstituer la distance à l'émetteur LOC (équation (3)). Cependant, du fait que ce signal n'intervient que comme perturbation de cette boucle de distance, la modélisation du signal glide n'a pas été étudiée. Nous avons utilisé un bruit dont le spectre est donné par l'équation (4) avec $\sigma = 10$ μA et $T = 0{,}5$ secondes, valeurs habituellement utilisées pour les simulations d'atterrissage automatique.

5 - MODELE DES BRUITS RECUEILLIS PAR LA RADIO-SONDE

Nous utilisons ici "bruits" au sens large, c'est-à-dire différence entre l'altitude mesurée par la radio-sonde et l'altitude géométrique réelle dans des axes liés à la piste, la référence étant par exemple l'altitude du seuil de la piste. Les "bruits" incluent donc le profil du terrain survolé, les perturbations radio-électriques de propagation de l'onde radio et les bruits propres du récepteur.

5.1 - Reconstitution du bruit de terrain

C'est à nouveau à partir des calculs de reconstitution de la trajectoire qu'on peut calculer le bruit recueilli par la radio-sonde. A l'aide des mesures effectuées par les cinéthéodolites, éventuellement corrigées par filtrage avec des informations d'accélération verticale issue d'une centrale à inertie, on reconstitue l'altitude de l'avion par rapport au seuil piste. On obtient alors le bruit de terrain par soustraction avec l'information de radio altitude. La figure 8 présente les profils de terrain ainsi calculés pour 2 pistes à Toulouse.

5.2 - Modèle du bruit de terrain

Le bruit de terrain est simulé par la somme de deux fonctions :

- Un bruit aléatoire décroissant à mesure que l'avion s'approche de la piste pour modéliser le fait que le terrain est en général plat aux abords du seuil de piste.
- Une pente moyenne du terrain. Nous reparlerons de cette pente moyenne dans la définition des caractéristiques géométriques des installations (chap. 7) car elle sera combinée aux autres erreurs afin que le calcul de la distance D_{mes} (équation (3)) soit perturbé au maximum.

Le spectre du bruit aléatoire avant multiplication par le gain décroissant avec la distance au seuil (cf. figure 9) est celui donné équation (4) avec

$$\sigma = 30 \text{ ft} \qquad T = 5 \text{ sec}$$

6 - RECHERCHE D'UN MODELE D'ERREURS DE LA CENTRALE INERTIELLE

6.1 - Description de la centrale inertielle utilisée

La centrale inertielle utilisée est du type I S S (ou I N S). AIR-INTER a choisi la centrale M G C 30 de SAGEM pour équiper ses AIRBUS. Ce système utilise une plate-forme stabilisée à quatre axes de cardan, asservie à rester horizontale. L'une des caractéristiques de ce type de centrale est de présenter, indépendamment des mouvements du véhicule qui la porte, une tendance à osciller avec la période dite de "Schüler" définie par :

$$T = 2\pi \sqrt{\frac{R}{g}} \tag{6}$$

où R est la distance au centre de la terre et g l'accélération de la pesanteur.

A la surface de la terre, on trouve T = 84 minutes. De ce fait, l'évolution des erreurs horizontales de vitesse présente une oscillation à cette période.

6.2 - Mesure des erreurs de vitesse

Le seul fait de mettre la centrale sous tension alors que l'avion reste immobile au sol déclenche l'oscillation de Schüler. La figure 10 donne les évolutions des deux composantes de la vitesse indiquée par la centrale MGC 30 alors que la vitesse réelle du véhicule est nulle. Nous avons donc directement les erreurs de vitesse de la centrale.

Nous constatons que les erreurs sur chacun des 2 axes sont indépendantes l'une de l'autre, et que leurs amplitudes sont aléatoires mais bornées. Ces erreurs correspondent tout à fait aux erreurs calculées par simulation de la centrale en introduisant les différents types d'erreurs des gyromètres, des accéléromètres et des erreurs de calage des axes sensibles de ces instruments (cf référence 5).

Les chiffres fournis par SAGEM pour la MGC 30 dont le cercle d'équi-probabilité (CEP) est de 2,5 NM/h, sont les suivants :

- erreur de vitesse : $\pm$ 14 kt
- dérive temporelle de cette erreur : $\pm$ 1 kt/mm (valeurs à 95 %)

6.3 - Modèle retenu

Les performances du filtre LISS dépendant en grande partie de sa capacité à résorber ces erreurs de vitesse, il a semblé intéressant de faire varier aléatoirement ces valeurs avec une répartition gaussienne de moyenne nulle. Les écarts-type sont les suivants :

- erreur de vitesse Nord ou Est $\sigma = 3,6$ m/s
- dérive temporelle des vitesses Nord ou Est $\sigma = 0,0043$ m/s2

chacune des erreurs sur les axes Nord ou Est étant non corrélées.

Compte tenu du fait que la durée de l'approche est limitée vis-à-vis de la période de Schüler (une approche dure 5 à 6 minutes au maximum) on pourra considérer que les vitesses inertielles indiquées peuvent s'écrire :

$$\begin{aligned} V_{NI} &= V_N + \Delta V_N + \gamma_N t \\ V_{EI} &= V_E + \Delta V_E + \gamma_E t \end{aligned} \tag{7}$$

où

ΔV_N, ΔV_E, γ_N, γ_E sont des constantes au cours d'une approche.

7 - CARACTERISTIQUES GEOMETRIQUES DE LA PISTE ET DES IMPLANTATIONS DES EMETTEURS ILS

Le terrain d'atterrissage est défini par les différents paramètres :

- γ_t pente moyenne de terrain avant le seuil de piste
- γ_g pente du faisceau glide
- S_1 sensibilité du faisceau Loc (en μA/ rd)
- d_{gl} distance entre émetteur loc et émetteur glide comptée le long de l'axe piste.
- d_{sg} distance entre émetteur glide et seuil de piste
- S_y sensibilité au point de repère ILS (seuil de piste) en μA/m.

Nous avons la relation :

$$S_y = \frac{S_1}{d_{gl} + d_{sg}} \tag{8}$$

Le terme S_y est imposé par l'O A C I à une valeur de 1,48 μA/m avec une tolérance de $\pm$ 0,25 μA/m (valeur à 95 %). La sensibilité du faisceau Loc S_1 varie donc beaucoup avec ($d_{gl} + d_{sg}$) c'est-à-dire avec la longueur de la piste. Trois cas ont donc été choisis, l'un représentatif d'une piste moyenne, les deux autres étant des cas extrêmes. Ils sont donnés figure 11. Nous y avons associés des pentes moyennes du terrain de telle sorte que le rapport $\frac{D}{S_1}$ permettant la transformation des écarts angulaires (en μA) en écarts métriques, soit correct dans un cas, maximum dans le 2ième cas, minimum dans le 3ième.

Pour tenir compte de la variation temporelle de la sensibilité du faisceau Loc, nous avons posé :

$$S_y = \bar{S}_y + \delta S_y \tag{9}$$

où S_y est le résultat d'un tirage aléatoire de moyenne nulle et d'écart-type σ = 0,125 μA/m. La valeur δS_y est constante au cours de l'approche.

8 - SIMULATION DE L'AVION,DU PILOTE AUTOMATIQUE ET DES DETECTEURS -

8.1 - Simulation de l'avion

Nous considérons que les équations latérales de l'avion sont peu influencées par son mouvement longitudinal. Le système est donc décrit par 3 équations linéarisées autour de la position d'équilibre, l'équation de force latérale, les équations de moment de roulis et lacet ; on obtient le système :

$$\begin{aligned}
\dot{\beta}_{sol} &= Y_\beta \cdot \beta_{aéro} + Y_p \cdot p_s + Y_r \cdot r_s + Y_\phi \cdot \phi_1 + Y_{\delta r} \cdot \delta r \\
\dot{p}_s &= L_\beta \cdot \beta_{aéro} + L_p \cdot p_s + L_r \cdot r_s + L_{\delta p} \cdot \delta p + L_{\delta r} \cdot \delta r \\
\dot{r}_s &= N_\beta \cdot \beta_{aéro} + N_p \cdot p_s + N_r \cdot r_s + N_{\delta p} \cdot \delta p + N_{\delta r} \cdot \delta r
\end{aligned} \tag{10}$$

Les angles d'Euler sont ensuite obtenus par intégration :

$$\begin{aligned}
\dot{\phi}_1 &= p_1 + tg\theta_0 \cdot r_1 \\
\dot{\psi} &= \frac{r_1}{\cos\theta_0}
\end{aligned} \tag{11}$$

où P_1 et r_1 sont les vitesses de roulis et lacet dans les axes avion alors que p_s et r_s sont les mêmes vitesses dans les axes de stabilité décalés de l'incidence α par rapport aux axes avion.

Nous avons aussi :

$$\beta_{aéro} = \beta_{sol} - \frac{v_v}{v_0} \tag{12}$$

où v_v est le vent latéral et la turbulence associée.

La vitesse latérale du centre de gravité est calculée ainsi :

$$\dot{y}_{cg} = V_0 \cdot \cos\gamma_0 \cdot \psi + V_0 \cdot \beta_{sol} - V_0 \cdot \sin\alpha_0 \cdot \phi_1 \tag{13}$$

d'où l'on déduit les coordonnées des différents points de l'avion.

8.2 - Simulation des organes de commande automatique du vol

Le but du système de commande automatique du vol est d'élaborer les différents ordres à appliquer aux servo-moteurs et aux servo-commandes des gouvernes de l'avion. Seul le pilote automatique latéral du constructeur SFENA a été simulé.

Il a été décomposé en équations tel que les différentes variables d'état internes apparaissent. Deux modes nous intéressent particulièrement :

- le mode maintien Loc, actif dès que l'écart Loc issu du récepteur Loc reste inférieur à 15 μA pendant 10 secondes. A partir de 700 ft, les gains de la boucle de base évoluent jusqu'aux valeurs du mode "LAND Track".
- le mode de décrabe qui permet d'annuler à partir de 30 ft, l'écart de cap dû à un vent de travers non nul.

Du fait que l'intégration des équations différentielles ainsi obtenues se fait avec un pas de 20 millisecondes, toutes les constantes de temps inférieures à 0,1 sec ont été supprimées ou regroupées entre elles afin qu'il y ait au moins un rapport de 5 entre la plus petite constante de temps simulée et le pas

de calcul.

8.3 - Simulation des détecteurs

Pour compléter la boucle de guidage de l'avion, il ne nous reste plus qu'à modéliser les différents détecteurs qui envoient leurs signaux au pilote automatique. Seuls ceux dont la fonction de transfert fait apparaître une constante de temps supérieure à 0,1 sec ont été simulés par un simple filtre passe-bas. Les différentes constantes de temps sont :

- 0,1 sec pour les récepteurs Loc, glide et radio sonde et pour le gyromètre de lacet,
- 0,15 sec pour l'accéléromètre latéral.

8.4 - Initialisation des variables d'état de l'avion et du P.A

- Les différentes variables d'état du pilote automatique sont initialisées de telle sorte que le système soit en équilibre à l'instant où le calcul est initialisé.
- Les variables d'état de l'avion sont aussi calculées de telle sorte que l'équilibre soit réalisé initialement. Ainsi :

$$\begin{aligned} &\cdot\ \beta_{sol} = \beta_{wind} = \frac{v_{v_0}}{V_0} \\ &\cdot\ \psi = -\beta_{wind} + R \\ &\cdot\ \phi_1 = 0 \end{aligned} \tag{14}$$

où v_{vo} est le vent moyen ; le dérapage aérodynamique est donc nul. Il reste deux variables à initialiser :

- y_{CG} : position latérale initiale de l'avion par rapport à l'axe piste,
- R : écart de route initiale par rapport au cap géographique ψ_{set}

Ces valeurs dépendent de la qualité du guidage de l'avion avant que ne commencent les calculs, c'est-à-dire pendant la phase de capture du faisceau Loc.

Nous avons choisi une initialisation par tirage aléatoire avec une répartition gaussienne de moyenne nulle et d'écart-type

- pour y_{CG} : $\sigma = 20$ m
- pour R : $\sigma = 2°$

9 - SIMULATION DU FILTRE LOC INERTIEL

Tous les calculs de simulation décrits jusqu'à maintenant (avion, pilote automatique, périphériques du P.A.) sont des calculs d'intégration d'équations différentielles du premier ordre. Ils doivent donc se faire avec un pas de calcul assez faible pour que la précision soit suffisante. Nous avons choisi un pas de 20 ms.

Pour simuler un calculateur numérique avec un autre calculateur numérique, il suffit de choisir le pas de calcul de la simulation égal au pas de calcul réel.

En effet, dans ce cas, les équations programmées dans le calculateur réel sont à reprendre sans rien changer, alors qu'une adaptation est nécessaire dans le cas contraire.

Du fait que les entrées de vitesse inertielle sont rafraichies par la centrale à inertie toutes les 0,2 sec, il était logique de choisir ce pas pour le calculateur LISS. Il faudra donc effectuer les calculs de l'avion et du pilote automatique 10 fois avant de calculer à nouveau le filtre LISS. Pendant ce temps, l'entrée $\hat{y}$ du P.A. sera constante (simulation d'un bloqueur d'ordre zéro).

Rappelons rapidement les équations du filtre de Kalman à observations discrètes :

. Intégration de l'équation d'état entre deux observations

$$\hat{X}_{n+1/n} = \phi(n+1,n) . \hat{X}_{n/n} + \Gamma_n . u_n \tag{15}$$

où ϕ est la matière de transition du système et Γ_n la matrice d'entrée.

. Intégration de la matrice de covariance correspondante

$$\Sigma_{n+1/n} = \phi(n+1,n) . \Sigma_{n/n} . \phi^T(n+1,n) + Q_n \tag{16}$$

où Q_n est la covariance du bruit sur l'état.

. Calcul du gain du filtre de Kalman

$$K_{n+1} = \Sigma_{n+1/n} . H^T . \left(H . \Sigma_{n+1/n} . H^T + R_{n+1}\right)^{-1} \tag{17}$$

où R_{n+1} est la covariance du bruit sur l'observation y_{n+1}

. Recalage des estimations à l'instant n + 1

$$\hat{X}_{n+1/n+1} = \hat{X}_{n+1/n} + K_{n+1} . \left(y_{n+1} - H . \hat{X}_{n+1/n}\right) \tag{18}$$

. Recalage de la matrice de covariance à l'instant n + 1

$$\Sigma_{n+1/n+1} = \left(I - K_{n+1} . H\right) . \Sigma_{n+1/n} . \left(I - K_{n+1} . H\right)^T + K_{n+1} . R_{n+1} . K_{n+1}^T \tag{19}$$

Ce sont ces équations (15) à (19), traduites en fonction du cas particulier à 4 variables d'état (cf chap. 2) qui ont été programmées en simulation. Dans le cas où les observations y_{n+1} (signal LOC) ne sont plus disponibles, seules les deux équations (15) et (16) sont calculées.

10 - APPLICATION DE LA SIMULATION A LA DEMONSTRATION DES PERFORMANCES

10.1 - Facilités offertes par la simulation

Afin de faciliter la démonstration de la validité de la simulation, plusieurs possibilités sont offertes par les programme de simulation. Ce sont :

- le tracé sur papier BENSON de toutes les variables intermédiaires nécessaires à des vérifications.

- la possibilité d'utiliser des enregistrements de vol comme entrées de la simulation ; par exemple, on peut après calcul de la trajectoire de l'avion au cours d'une approche, puis des bruits LOC et des vents, réintroduire ces derniers dans la simulation et comparer avec les résultats de vol.

- le calcul au cours de l'approche d'une variable d'état de l'avion représentant sa trajectoire potentielle :

$$X_{Avion} = \left| y_{ca} + K_1 . R + K_2 . \phi_1 \right| \tag{20}$$

- la possibilité d'enchaîner plusieurs approches l'une à la suite de l'autre avec des perturbations répétitives qui ne dépendent que d'une suite de 10 nombres aléatoires pour l'initialisation du processus. On peut donc comparer le comportement de la boucle de guidage pour des paramètres de réglage différents, mais vis à vis de perturbations identiques.

- le calcul de variables statistiques sur un certain nombre de simulations d'approches successives. Il est possible de calculer, par exemple, moyenne et écart-type de :

. l'écart latéral à 100 ft, à 15 ft et à l'impact,

. l'assiette latérale à l'impact,

. la vitesse transversale du train à l'impact.

....

Par ailleurs, on calcule également un paramètre dénommé facteur λ qui caractérise l'aptitude de l'avion et du P.A. à suivre un signal. Sa valeur est :

$$\lambda_x = \sqrt{\frac{\sum_1^n Max(x_i^2)}{2n}} \tag{21}$$

où x est la variable à étudier, par exemple $\eta_{mes}, \hat{\eta}, \eta_{vrai}$
et n est le nombre d'approches simulées.

- la comptabilisation des approches ayant entraîné soit l'allumage des écarts excessifs LOC ($\eta_{mes} \geqslant 20$ μA pendant plus de 0,5 secondes) soit l'allumage du voyant AUTOLAND demandant l'interruption de l'atterrissage automatique (écarts excessifs et $h \leqslant 200$ ft).

10.2 - Simulations réalisées pour les démonstrations statistiques

A chacune des deux possibilités de vent (vent moyen et vent fort), nous avons associé les trois cas de longueur de piste, soit donc six cas différents. Chacun de ces 6 cas a fait l'objet de 100 simulations d'atterrissage, chaque approche étant caractérisée par des turbulences atmosphériques, des bruits LOC, des erreurs de centrale, une sensibilité LOC et des valeurs d'initialisation de la position avion toutes différentes les unes des autres et obéissant aux lois définies plus haut. Au total 600 approches ont été simulées pour démontrer les performances du guidage hybride LISS par rapport à 600 approches effectuées dans les mêmes conditions et avec les mêmes perturbations en guidage à l'aide du signal LOC brut (guidage LOC).

La référence (1) donne les performances comparées des deux modes de guidage avec un filtrage Loc-Inertiel correspondant aux deux objectifs initialement fixés, à savoir filtrage des distorsions du faisceau LOC et servie à une panne LOC. Nous allons maintenant examiner les nouvelles possibilités du filtrage Loc-Inertiel en ce qui concerne la détection des décalages de l'axe moyen du faisceau LOC.

11 - DETECTION D'UN FAISCEAU LOC DECALE DE L'AXE PISTE

11.1 - Objectif de la détection d'un décalage de faisceau

Il s'agit de permettre à l'avion d'atterrir sur une piste équipée en catégorie II avec des minima de visibilité de catégorie III. L'Airbus est certifié avec une hauteur de décision de 15 ft et une portée visuelle de piste de 100 m avec les équipements nécessaires à un atterrissage de catégorie III.

Le but est donc de pouvoir atterrir avec cette hauteur de décision que la piste soit agréée de catégorie II ou de catégorie III.

Un ILS de catégorie II est équipé d'un seul émetteur LOC et d'une surveillance de l'émission dont le capteur est placé à quelques centimètres des aériens d'émissions, alors qu'un ILS de catégorie III français a un émetteur normal, un émetteur de secours avec une surveillance interne, une surveillance de l'émission triplée avec vote permettant de changer d'émetteur, un test opérationnel des moniteurs de surveillance afin de détecter les pannes cachées et enfin une autre surveillance "lointaine" de l'émission placée de l'autre côté de la piste et qui surveille la propagation sur la piste.

Le but de la détection d'un axe LOC décalé à l'aide du système LISS est donc de rétablir par une surveillance externe, le niveau d'intégrité du signal LOC émis par un ILS de catégorie II, de telle sorte que les probabilités de pannes cachées soient identiques. Par ailleurs, le système hybride radio-inertie permet, grâce à sa fonction survie, de rétablir la continuité du service en cas de panne de l'émetteur LOC qui n'est pas doublé en catégorie II.

Du fait que avec un faisceau de catégorie II, la hauteur de décision demandée est supérieure

à la hauteur minimale d'interruption d'approche (HMIA = 15 ft). Il faut donc détecter à coup sûr un décalage du faisceau qui amènerait l'avion à rencontrer un obstacle au cours de la remise de gaz puisqu'on est sûr qu'il ne touchera pas le sol, plat aux abords immédiats de la piste. Le premier obstacle existant est l'antenne d'émission du signal glide. Cette antenne est vue depuis l'antenne LOC sous un angle d'environ deux degrés par rapport à l'axe médian de la piste.

11.2 - Conditions nécessaires d'une bonne détection d'un faisceau décalé

11.2.1 - Expression de l'erreur de vitesse transversale

La vitesse latérale réelle de l'avion est donnée par la relation :

$$\dot{y} = V_E \cos \psi_{set} - V_N \cdot \sin \psi_{set} \tag{22}$$

alors que celle calculée dans le filtre LISS est la suivante :

$$\dot{Y}_I = V_{EI} \cdot \cos R_f - V_{NI} \cdot \sin R_f \tag{23}$$

Les erreurs des vitesses Nord et Est de la centrale s'expriment par ailleurs :

$$ev_n = V_{NI} - V_N \tag{24}$$

$$ev_e = V_{EI} - V_E$$

Posons $R_f = \psi_{set} + \delta R_o$ - L'erreur de vitesse transversale est donc, compte tenu du fait que l'angle δR_o est petit :

$$ev_T = \dot{y}_I - \dot{y} = ev_e \cdot \cos \psi_{set} - ev_n \cdot \sin \psi_{set} + \delta R_o (V_{Lo} - V_L) + \delta R_o \cdot (-ev_e \cdot \sin \psi_{set} - ev_n \cdot \cos \psi_{set} - V_{Lo})$$

où V_{10} est la vitesse longitudinale de l'avion V_1 à l'instant d'initialisation des calculs.

En approchant chacune des erreurs de vitesse Nord ou Est par un terme constant et une dérive en fonction du temps (expression (7)), on trouve :

$$ev_T = \Delta V_T + \gamma_T \cdot t + \delta R_o \cdot (V_{lo} - V_l) \tag{25}$$

où ΔV_T, γ_T, δR_o sont des constantes et $(V_{l_o} - V_l)$ est l'écart de vitesse par rapport à la vitesse de l'avion à t = 0

Cette décomposition explique les différentes variables d'état estimées par le filtre LISS (cf § 2.2).

Dans le cas où le faisceau LOC est décalé d'un angle $\Delta\eta$ de l'axe de la piste, on démontre facilement que la seule façon pour isoler ce décalage est que la référence de projection des vitesses R_f coïncide exactement avec le cap géographique de la piste ψ_{set}. On a alors :

$$\widehat{\Delta V_T} = V_{lo} \cdot \Delta\eta + \Delta V_{T_o} \tag{26}$$

$$\widehat{\delta R_o} = -\Delta\eta$$

L'expression (25) montre également qu'on ne pourra isoler l'erreur δRo du terme constant ΔV_T que si l'écart de vitesse $V_{lo} - V_l$ est assez important pour que les estimations du filtre aient suffisamment convergé.

11.2.2 - Influence du niveau des bruits LOC

L'évaluation du décalage du faisceau LOC doit être faite avec une précision assez grande afin que le test ait un sens. Comme on doit avoir une probabilité très faible de détecter un décalage de faisceau alors que ce décalage n'existe pas, mais aussi du fait qu'il faut détecter un décalage de 2° avec une probabilité voisine de 1, nous avons choisi le seuil à partir duquel le faisceau sera jugé décalé à 1° . En arrivant à une précision de l'estimation $\widehat{\Delta\eta}$ tel que son écart type soit de 0,2° , nous sommes sûrs que les probabilités seront correctes.

Le réglage du filtre basé sur les objectifs de filtrage et de survie, dénommé réglage 1 (réf. (1)) est basé sur une évolution de la covariance du bruit LOC donnée figure 12. Les écarts types de l'estimation du décalage de faisceau sont portés figure 13 dans plusieurs cas d'évolution de vitesse, c'est-à-dire plusieurs cas de procédure d'approche. On voit également l'influence du niveau des bruits LOC effectivement rencontrés. Nous constatons que ce réglage ne permet pas une précision sur $\widehat{\Delta\eta}$ suffisante.

Un deuxième réglage du filtre LISS où la programmation du bruit LOC est donnée figure 12 a donc été étudié pour arriver à une précision suffisante. On s'aperçoit sur la figure 13 que ce réglage ne donne satisfaction que dans le cas où le bruit LOC effectivement rencontré correspond à la programmation du filtre. Il est donc nécessaire d'implanter, dans le calculateur LISS, un circuit de mesure du bruit LOC effectivement rencontré, afin de savoir quelle confiance accorder au décalage du faisceau que le filtre évalue. Ce circuit calcule l'écart-type du signal ($\eta_{mes} - \hat{\eta}$) qui est une bonne approximation du bruit LOC. La figure 14 donne le résultat de ce calcul dans le cas des deux bruits LOC étudiés précédemment. Le seuil choisi pour le niveau du bruit LOC est de 3 µA. Au delà, on considèrera que le faisceau LOC est trop bruité pour que l'estimation du décalage de l'axe soit assez précise.

12 - MISE EN OEUVRE DU SYSTEME LISS DEFINIF

12.1 - Actions de l'équipage avant le début de l'approche

L'équipage aura à sa disposition, sur un boîtier spécial :

- un contacteur à 3 positions, à savoir :
  - . LISS "OFF" ou guidage LOC : position 1
  - . LISS Réglage 1 "ON" : position 2
  - . LISS Réglage 2 "ON" : position 3
- une molette à 4 digits pour avoir une précision de 0,1° permettant d'afficher le cap géographique de la piste.

Avant la capture LOC, il faudra donc choisir la position du contacteur. Dans les 2 premières positions, la hauteur de décision sera la hauteur de décision actuelle. Dans la troisième position, la hauteur de décision sur un ILS de catégorie II est diminuée.

12.2 - Organisation du test "DECALAGE DU FAISCEAU"

Ce test est présenté figure 15. Dans le cas où on désire une hauteur de décision diminuée, plusieurs actions s'enchaineront :

- vérification que le cap géographique de la piste a bien été affiché avant le début des calculs.

- à 200 ft, un test sur la procédure suivie permet de savoir si la décélération a été suffisante ($V_{10} - V_1 \geqslant 50$ kts) et si le temps de filtrage a été assez grand pour que les estimations soient correctes.

Un autre test sur le bruit LOC évalué au cours de l'approche permet de savoir si on peut faire confiance au décalage de faisceau évalué. Si un de ces tests n'est pas correct, une alarme préviendra l'équipage pour que la hauteur de décision soit remontée à sa valeur nominale.

- à 100 ft, test sur le décalage de faisceau et allumage de l'alarme "AUTOLAND" si le décalage estimé est supérieur à 1°. Dans le cas contraire, l'approche est poursuivie jusqu'à la hauteur de décision, altitude à laquelle le pilote fait le choix entre soit remettre les gaz, soit continuer l'approche si la visibilité le permet.

13 - CONCLUSION

La simulation prend de plus en plus de place dans la démonstration des performances d'un système embarqué. Ces avantages ne sont pas négligeables tant pour la facilité de modification, la possibilité de faire des études comparatives, la possibilité d'étudier des cas limites qu'il serait difficile de rencontrer en vol, que pour le coût plus faible à l'époque où les essais en vol deviennent très coûteux.

Le but de cet exposé était de démontrer que l'étude d'un système nouveau pouvait se faire à l'aide de cet outil pourvu que la simulation soit représentative des phénomènes réels, en particulier en ce qui concerne les perturbations de la boucle d'asservissement concernée.

Le système hybride Loc-Inertiel de guidage latéral d'un avion qui vous a été présenté répond aux trois objectifs fixés, c'est-à-dire le filtrage des distorsions du faisceau LOC, la survie à une panne de l'émetteur LOC et enfin la détection d'un faisceau LOC dévié. Pour permettre la réalisation du 3ᵉ objectif, il a été nécessaire d'évaluer en temps réel le niveau des bruits LOC que l'avion rencontre. Le respect d'une procédure d'approche en ce qui concerne l'évolution de la vitesse et la distance de la capture LOC, permet d'évaluer le décalage du faisceau LOC avec une précision suffisante et d'en avertir l'équipage. Une surveillance externe, totalement indépendante de celle qui existe dans l'ILS, peut donc être assurée par le système, qui pourrait ainsi permettre des opérations de catégorie III sur des ILS de catégorie II.

Ultérieurement, le système pourrait également permettre d'obtenir une hauteur de décision nulle sur des ILS de catégorie III pourvu qu'il soit associé à un système de confirmation de la position de l'avion pour s'assurer que le guidage ILS a amené l'avion au-dessus de la piste.

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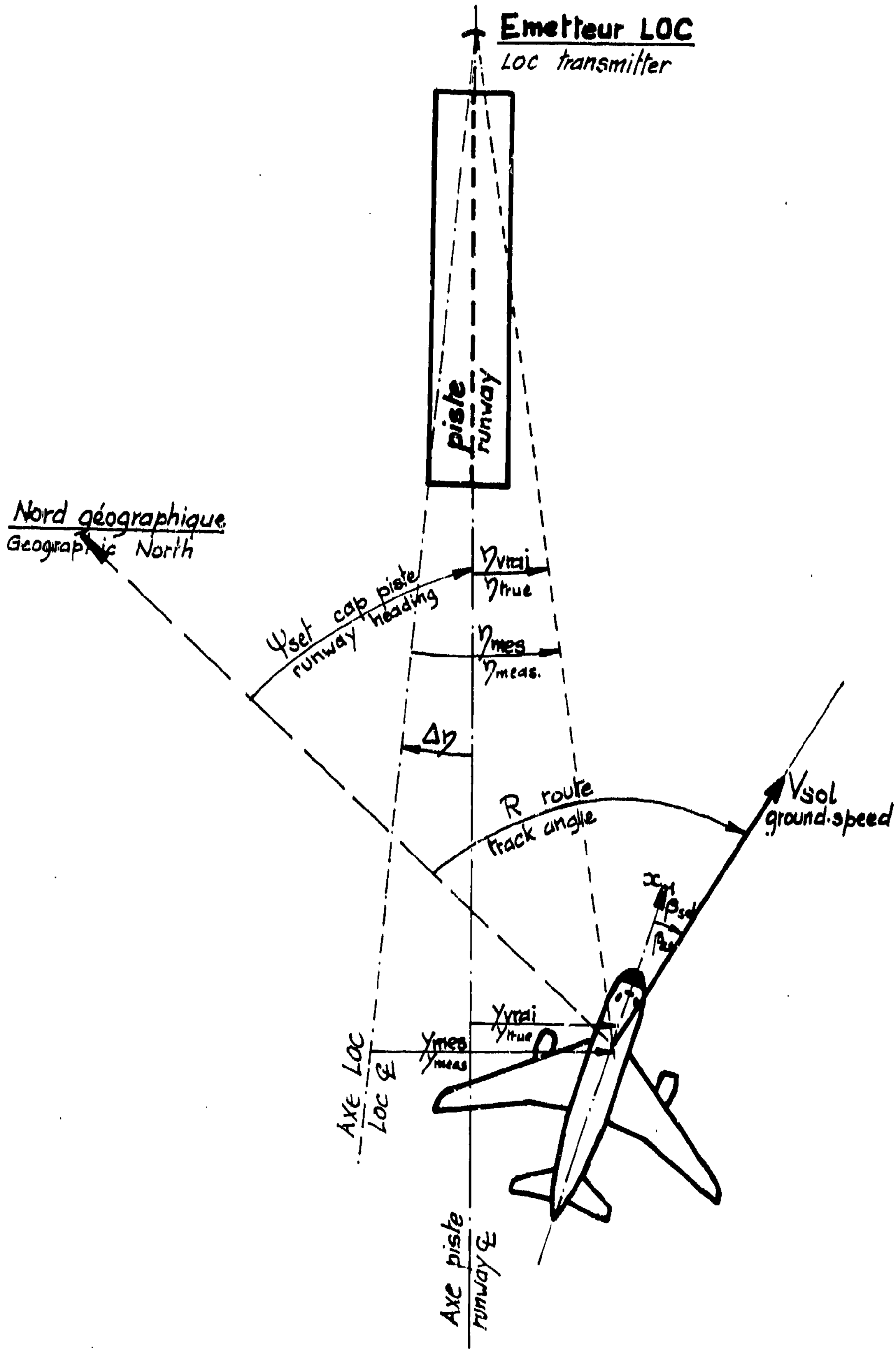


Fig.1 Principe du fonctionnement du système LISS

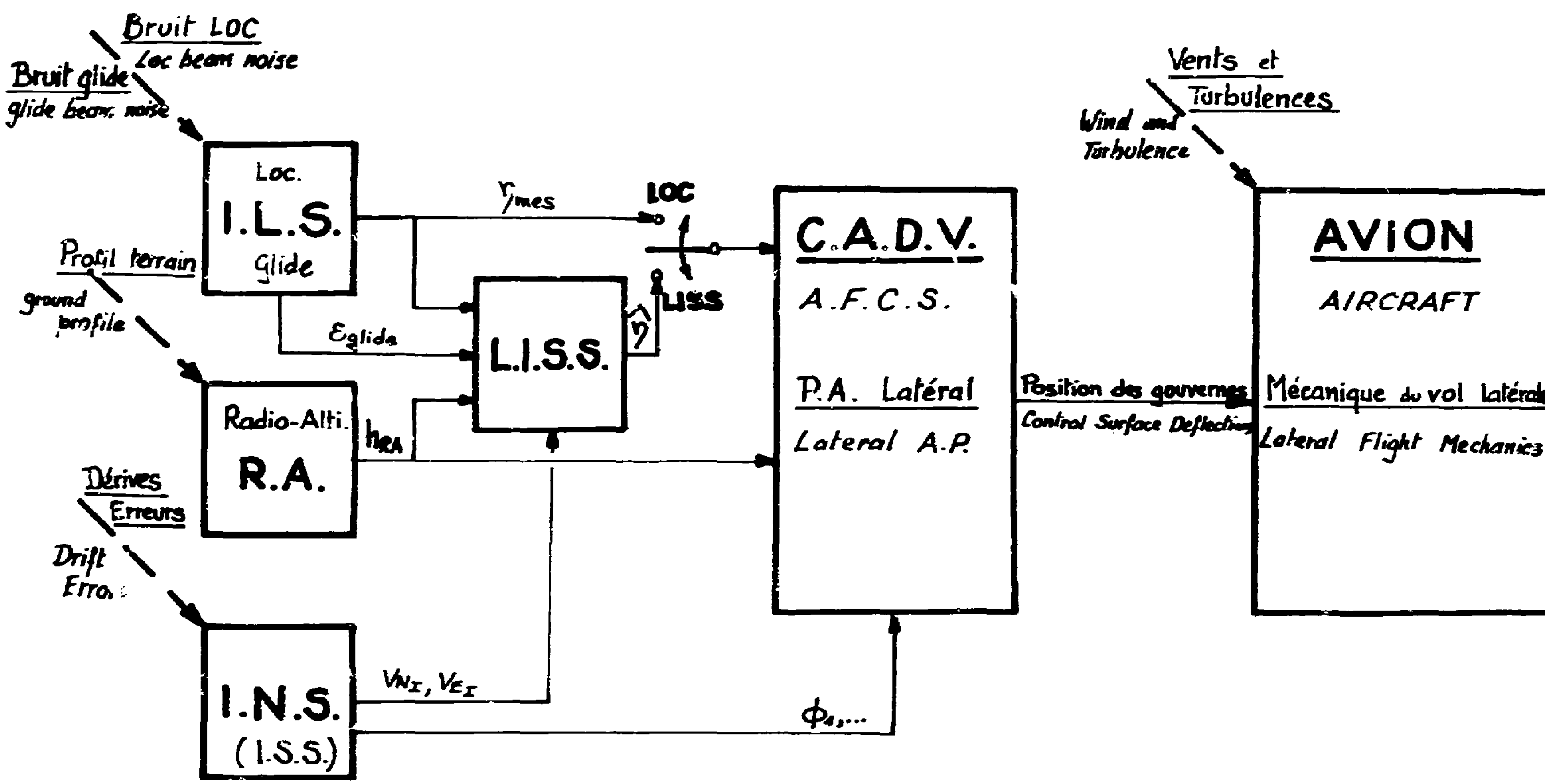


Fig.2 Intégration du système LISS dans l'avion

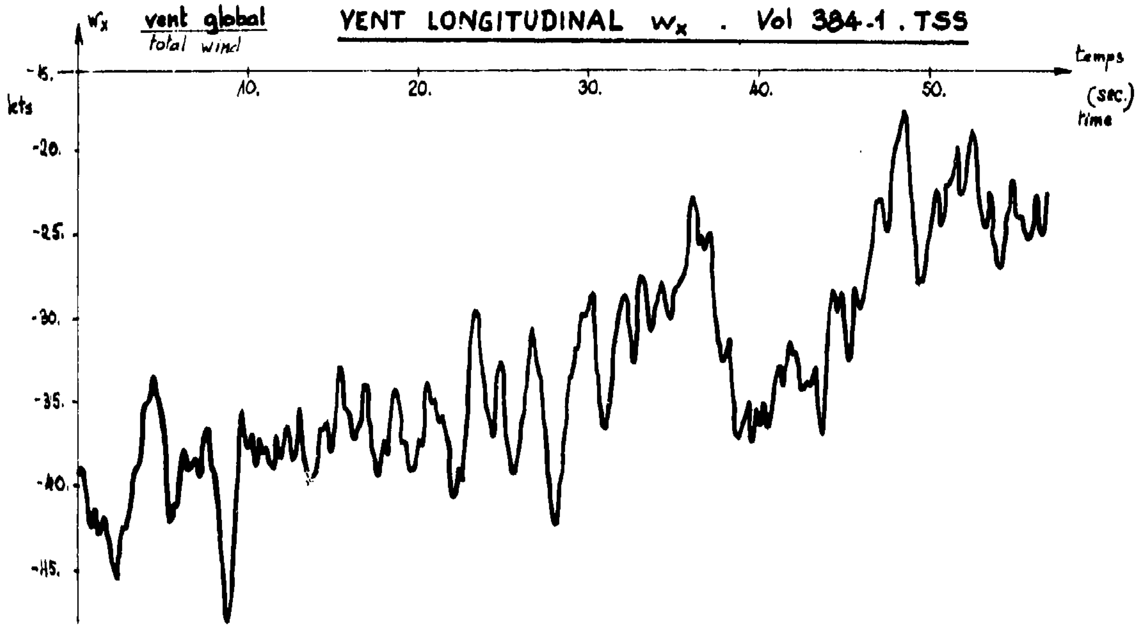


Fig.3a Exemple de vent longitudinal mesuré Wx

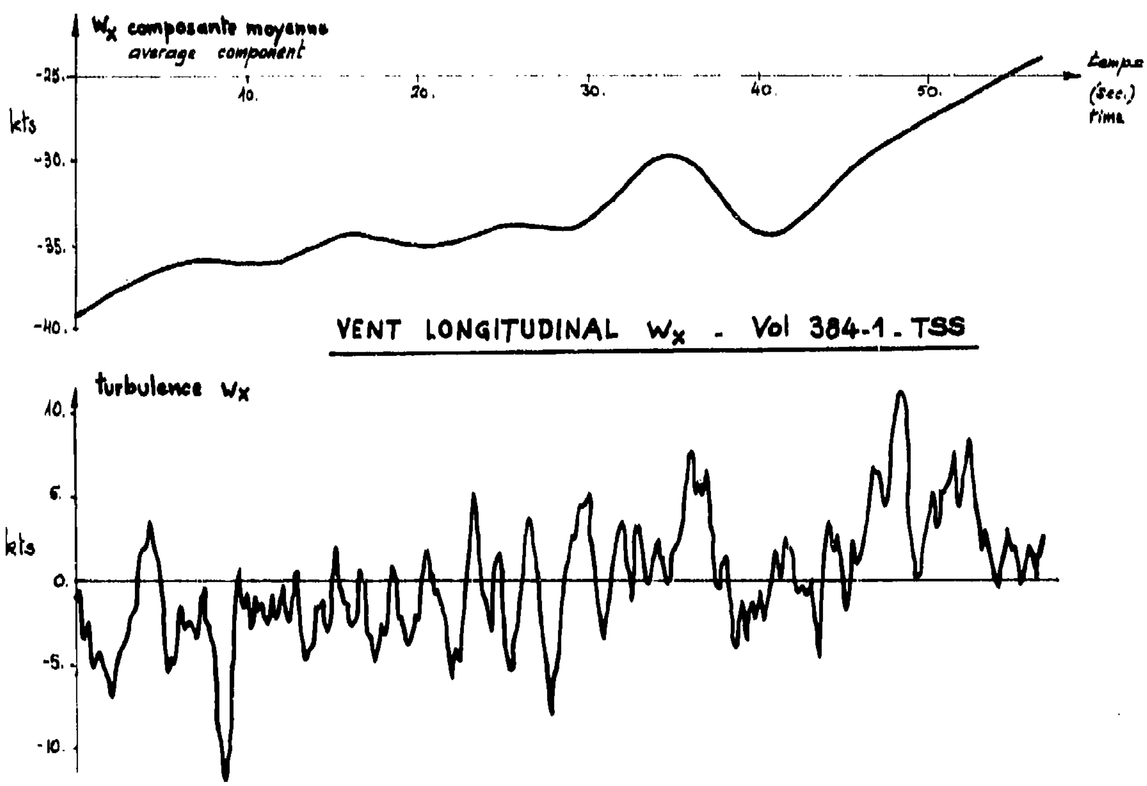


Fig.3b Filtrage du vent longitudinal pour isoler la composante moyenne

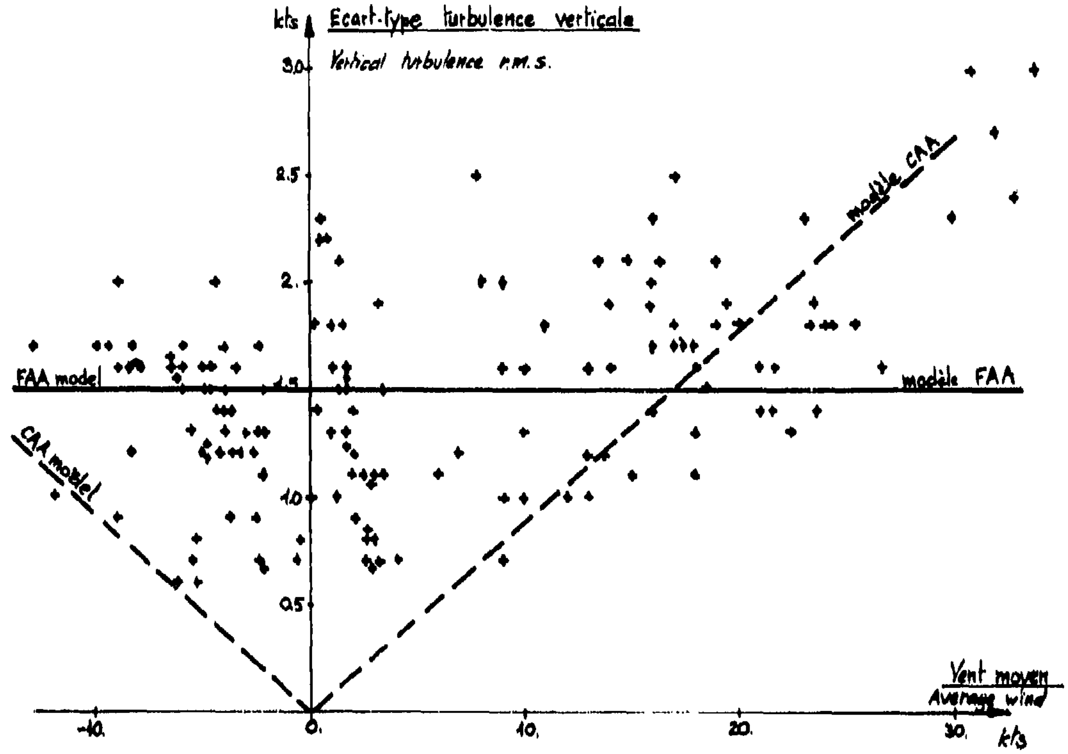


Fig.4a Corrélation entre la turbulence verticale et le vent moyen

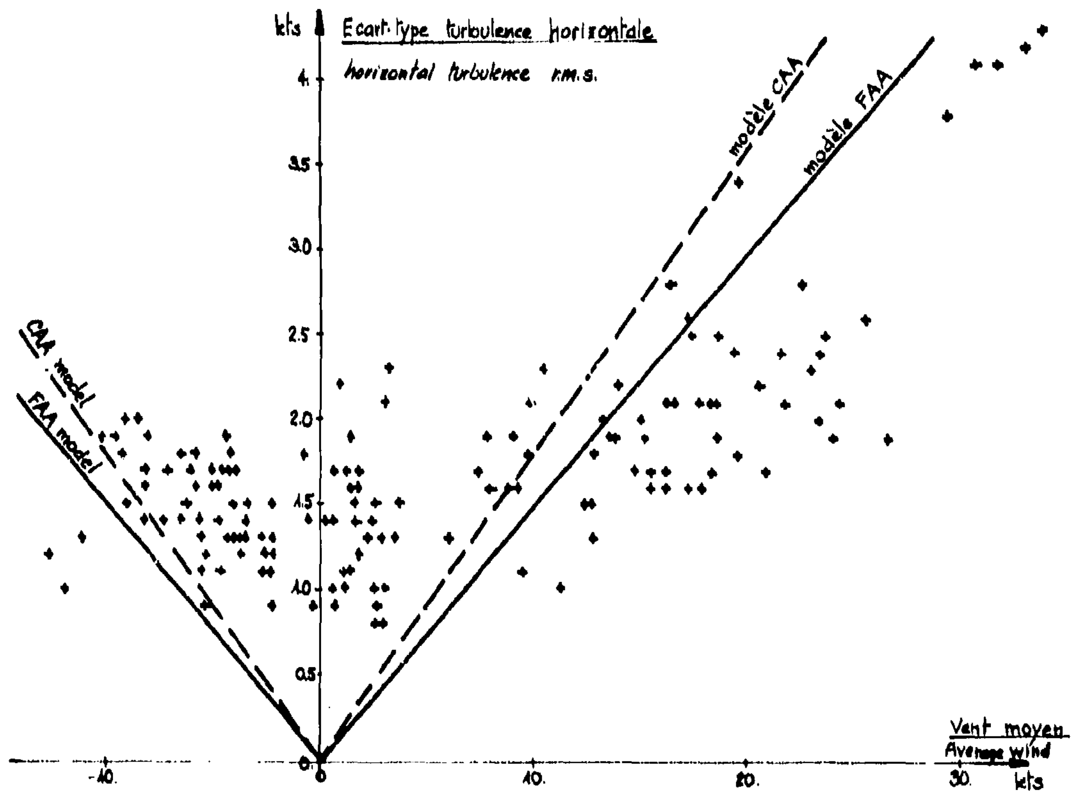


Fig.4b Corrélation entre la turbulence horizontale et le vent moyen

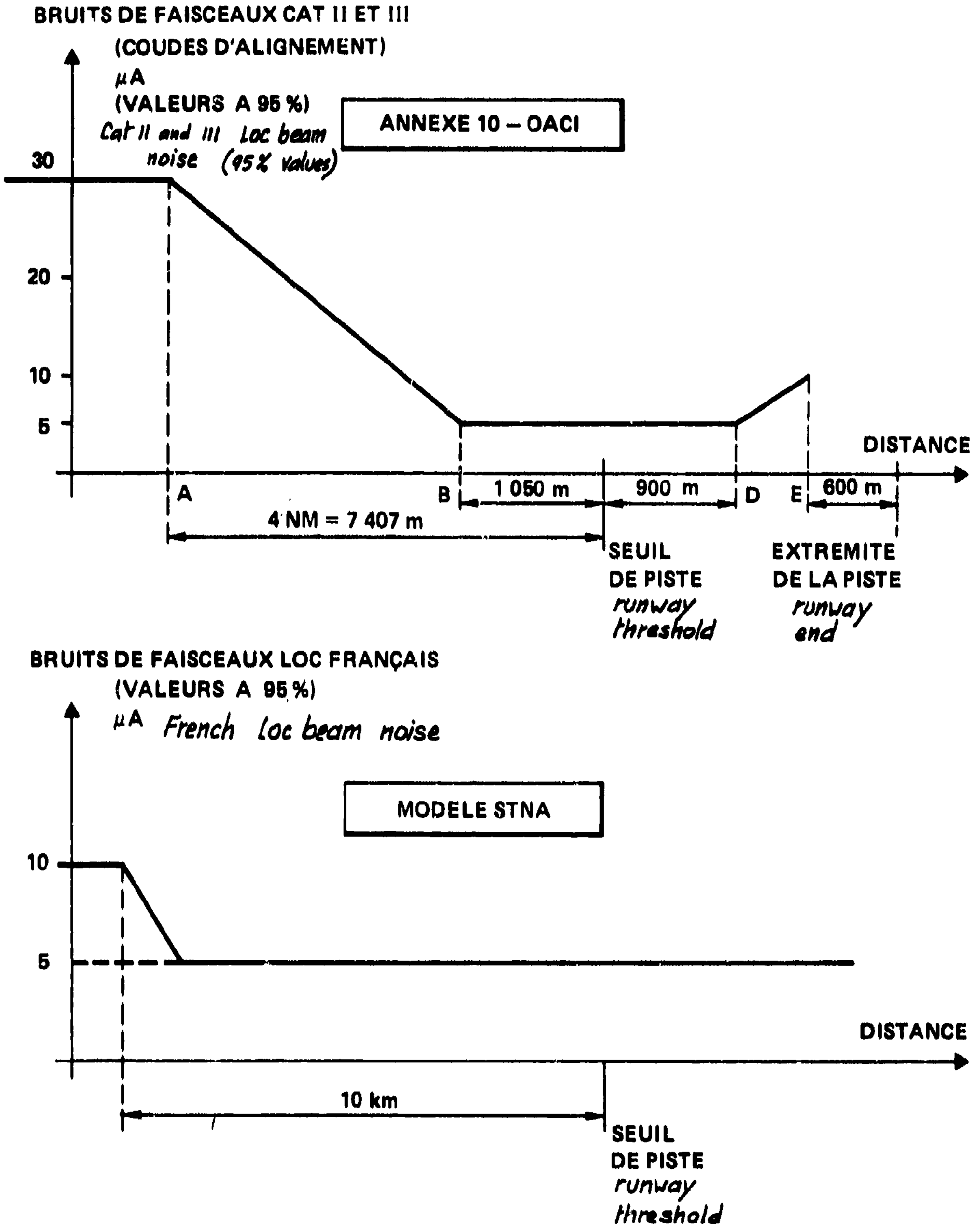
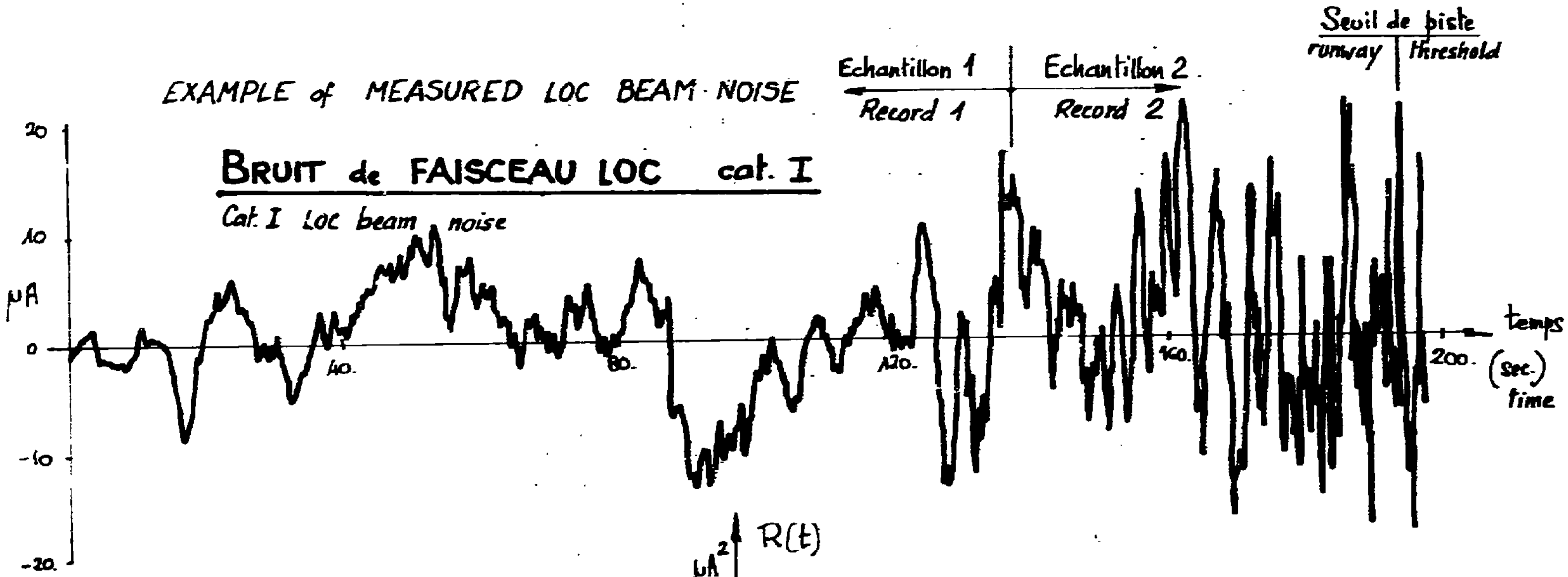


Fig.5 Modèles de bruits de faisceaux LOC



	Echantillon n° 1	Echantillon n° 2	Echantillon global
Moyenne m average µA	+ 0.4	+1.13	+ 0.59
Ecart-type σ r.m.s. µA	5.17	8.99	6.57
C^te de temps T time c^t sec	4.1	0.6	1.3

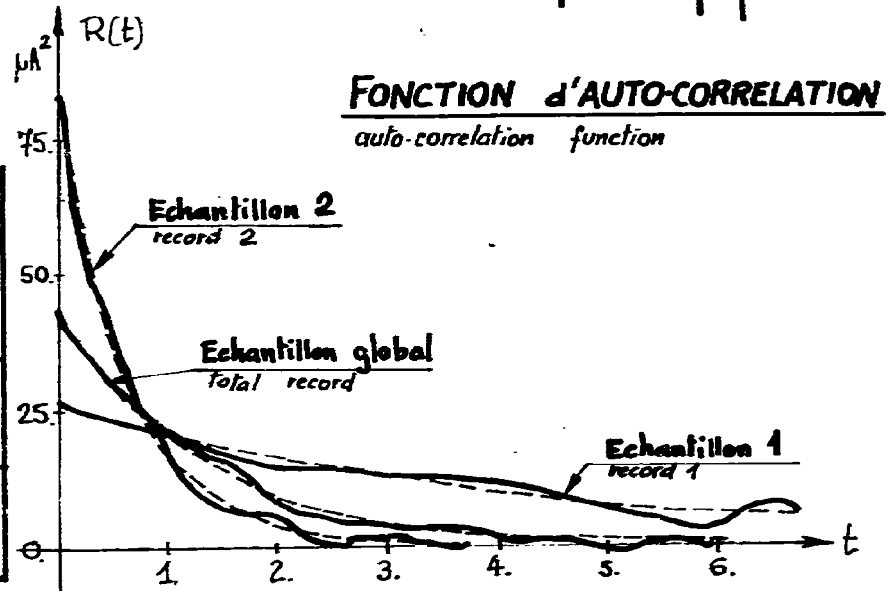


Fig.6 Exemple de bruit LOC mesuré

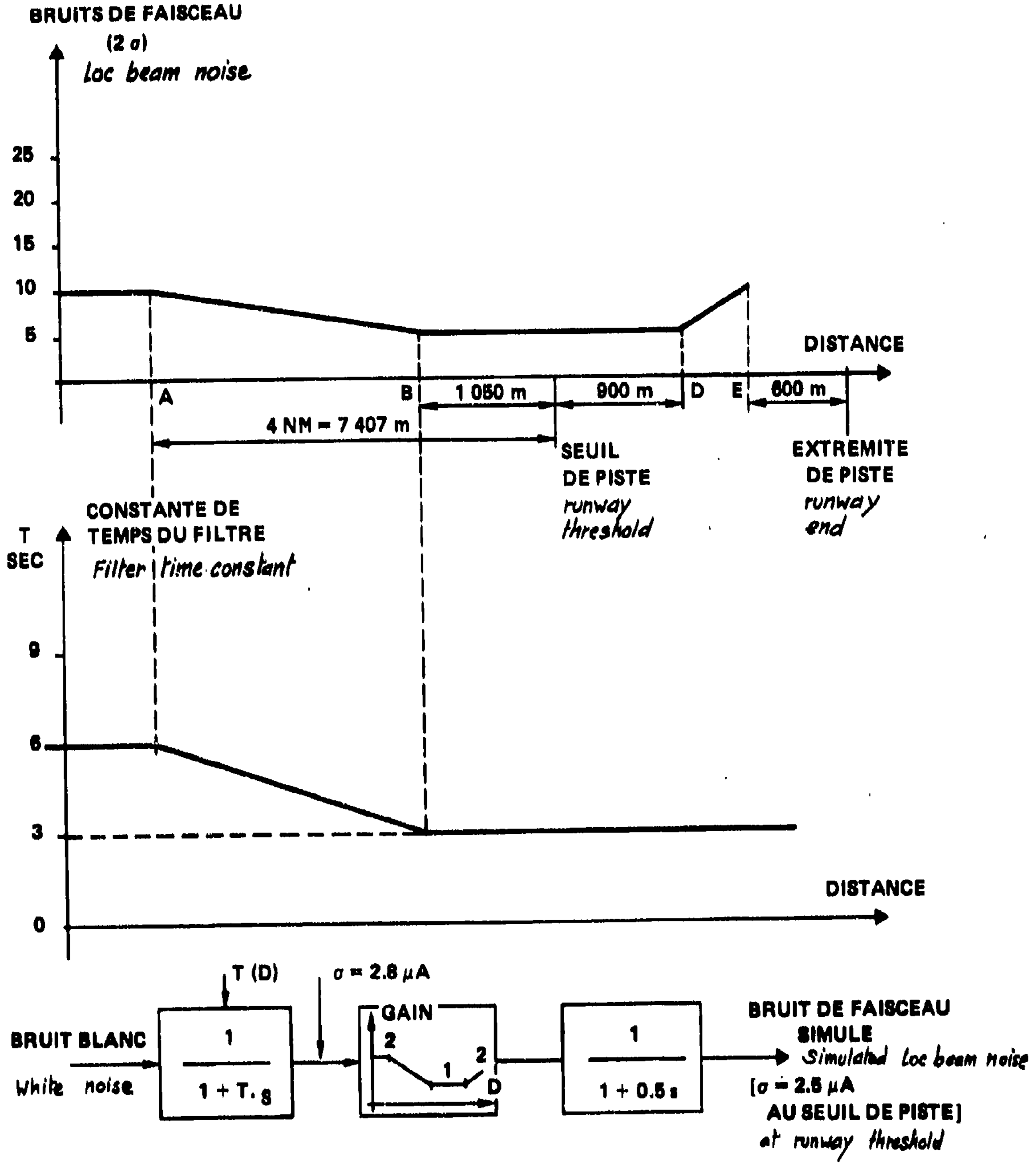


Fig.7 Modèle de bruit de faisceau proposé

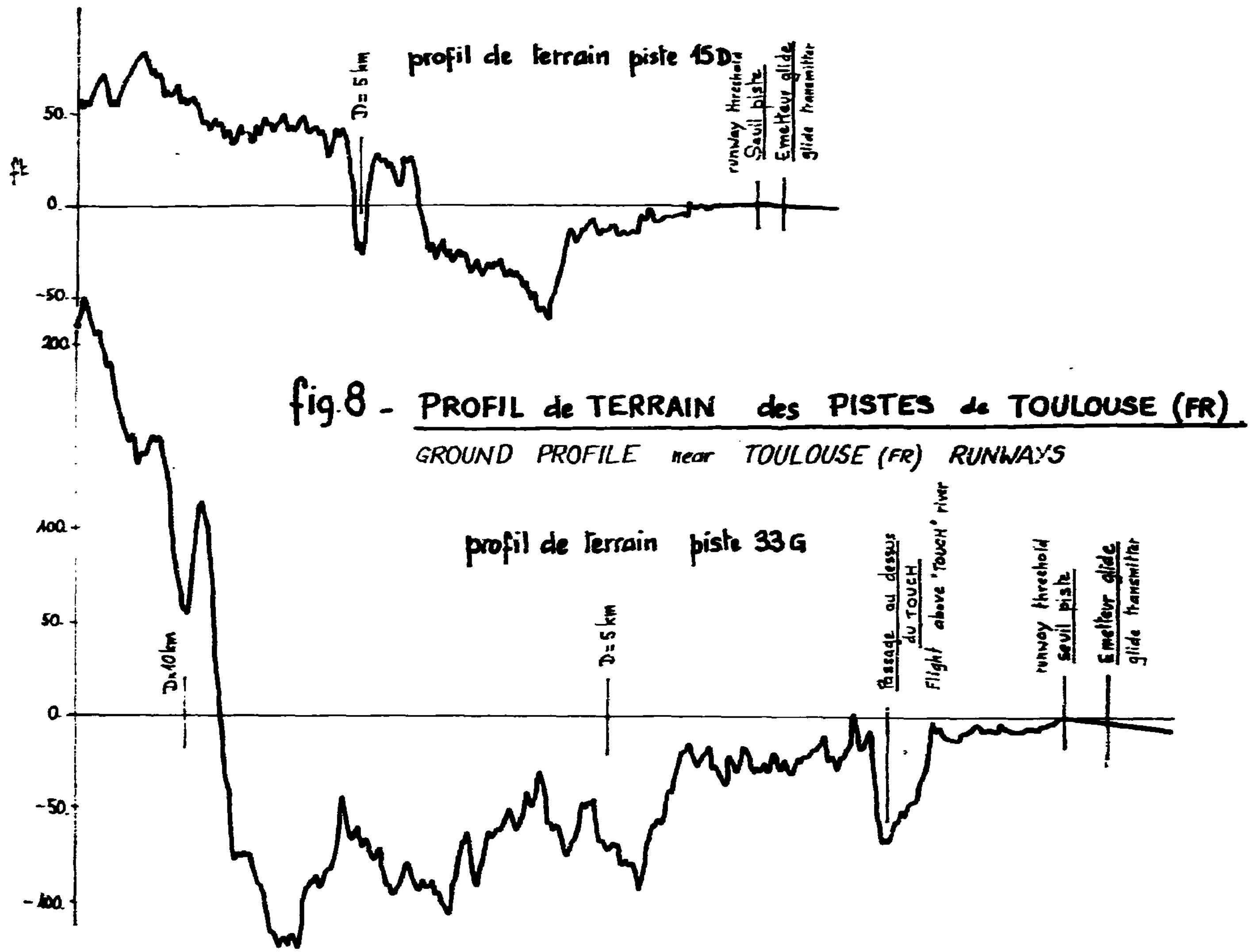


Fig.8 Profil de terrains des pistes de Toulouse (FR)

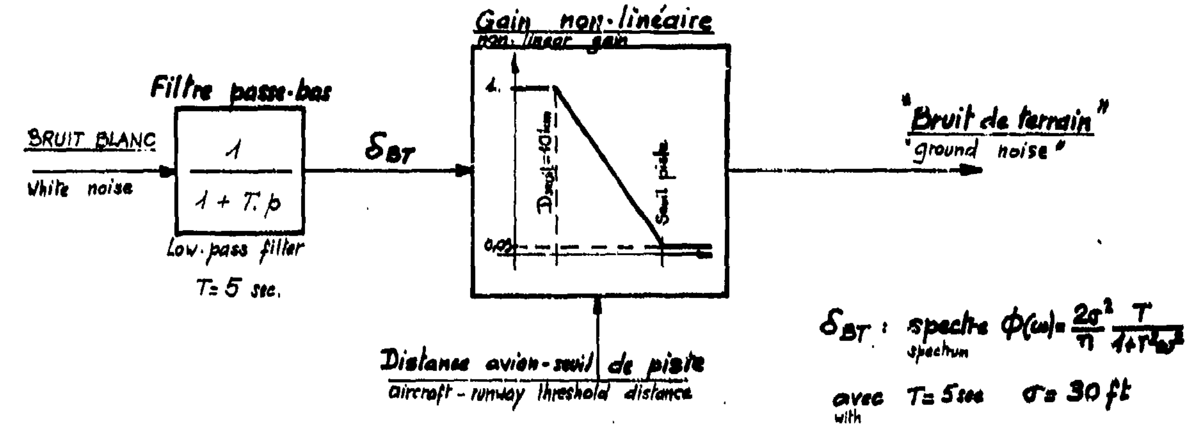


Fig.9 Simulation du "bruit de terrain"

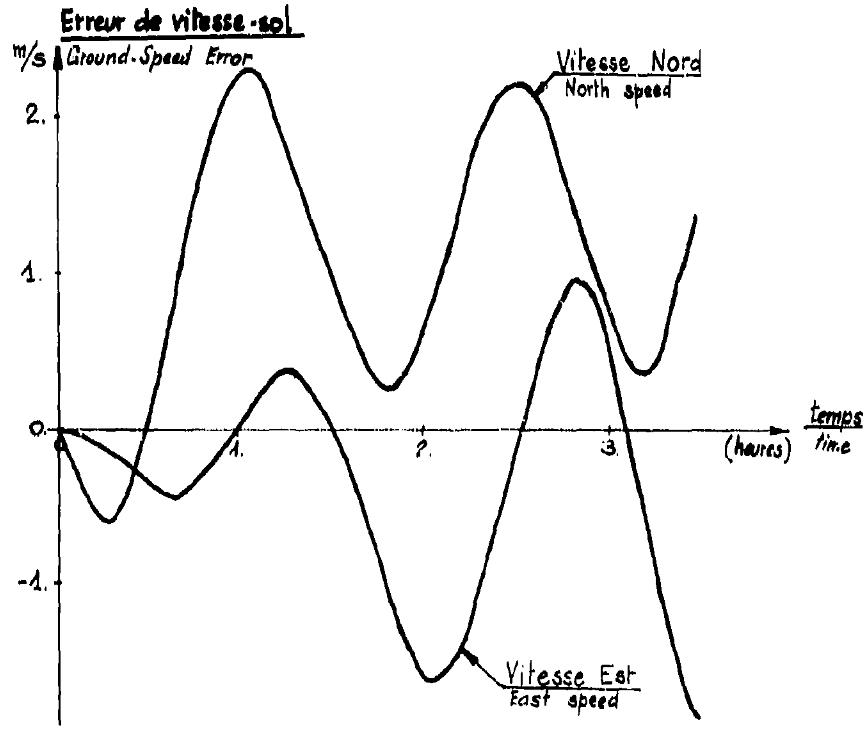
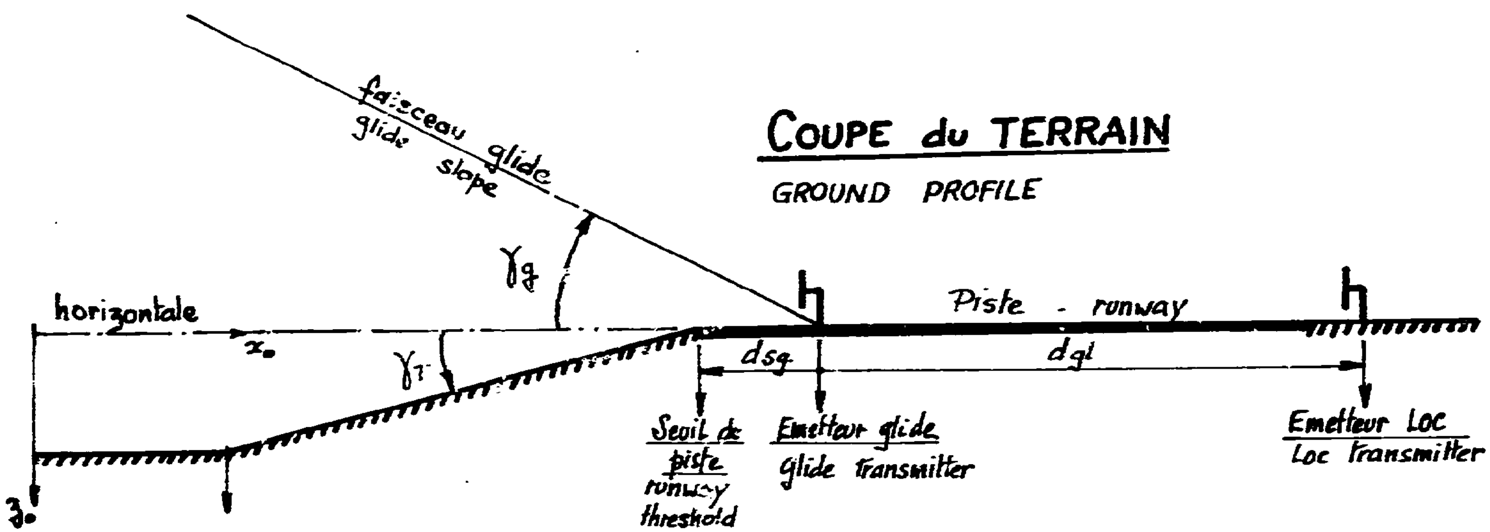


Fig.10 Exemple d'évolution des erreurs de vitesse d'une centrale à inertie



	Piste courte short runway	Piste moyenne Average-length runway	Piste longue long runway
γ_g	$-2.5°$	$-2.8°$	$-3.0°$
d_{sg}	400 m	400 m	400 m
d_{gl}	1920 m	2500 m	3470 m
$\bar{S}_{Loc}$	60 µA/deg.	75 µA/deg.	100 µA/deg.
γ_T	$-0,8°$	$0.°$	$+1.0°$

Fig.11 Caractéristiques géométriques et radio électrique des terrains d'atterrissage

	$\sigma^2 . T$ $\mu A^2 . sec$ au seuil piste / at runway threshold	$D > 4$ NM
Bruits loc de certification (cat III) / Certification loc noise	3,1	3,1
Bruits Loc forts Cat II et III / Strong Loc beam noise	18,7	150.
Programmation filtre Réglage 1 / Filter programming	48.	768.

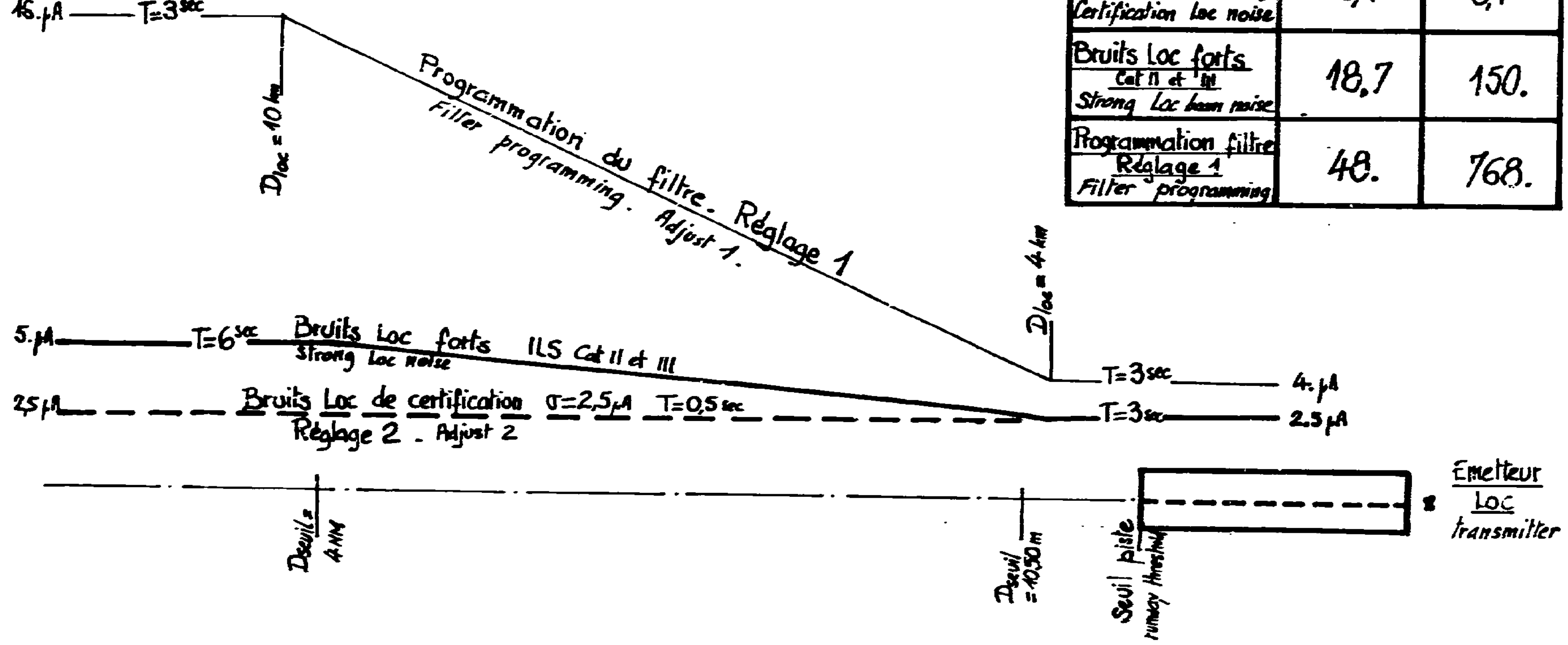


Fig.12 Programmations de la covariance du bruit LOC pour les différents réglages du filtre

- Test "décalage de faisceau" $\widehat{\Delta\eta} > \delta$

  Loc beam centerline deflection test

$$\delta = 1°$$

- Précision nécessaire

  Needed accuracy

$$\sigma_{\Delta\eta} = 0{,}2°$$

- Influence des bruits de faisceau, du réglage, de la procédure sur $\sigma_{\Delta\eta}$

  Loc beam noise, filter adjusting and procedure influence on $\sigma_{\Delta\eta}$

Réglage 1 / Adjust 1	Procedure 1 $\Delta V = 27$ kts	Procedure 2 $\Delta V = 74$ kts	Procedure 3 $\Delta V = 54$ kts
Bruits Loc forts / Strong Loc noise	1,7°	0,85°	1,0°
Bruits Loc faibles / Mild loc noise	1,5°	/	/

Réglage 2 / Adjust 2	Procedure 3 $\Delta V = 54$ kts
Bruits Loc forts / Strong Loc noise	0.8°
Bruits Loc faibles / Mild Loc noise	0.15°

Fig.13 Précision de l'estimation du décalage de faisceau LOC

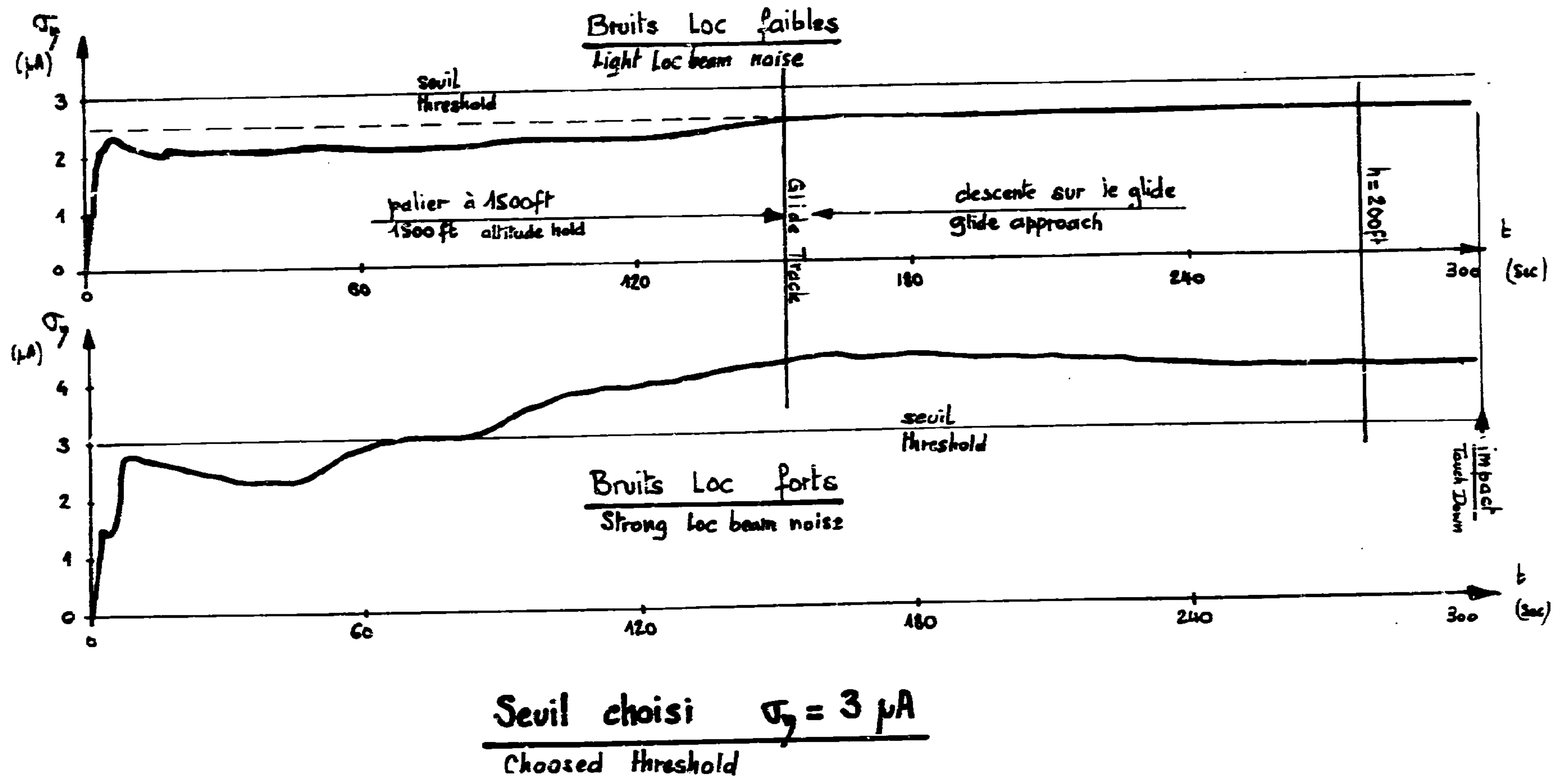


Fig.14 Evaluation du niveau du bruit LOC rencontré en voi

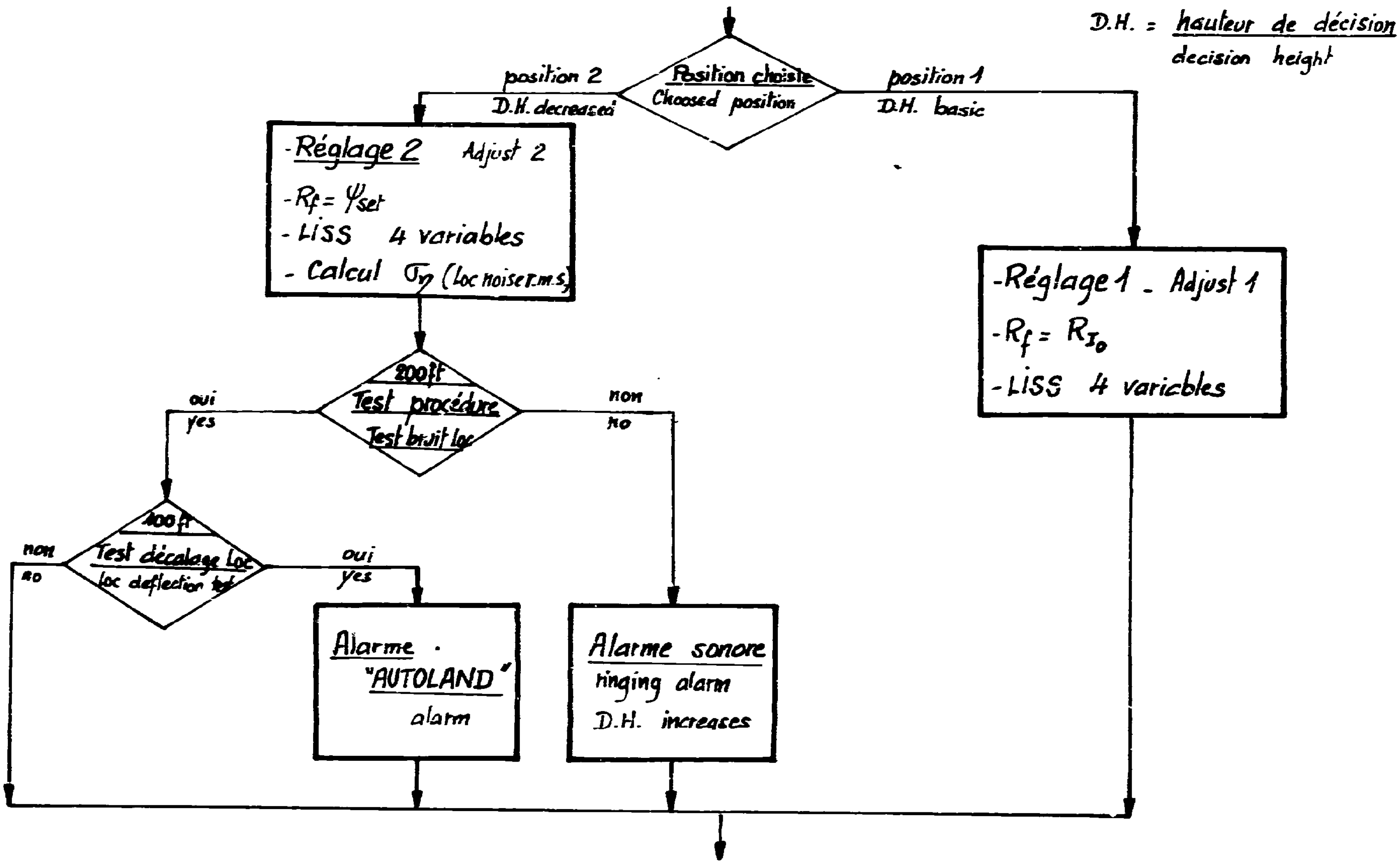


Fig.15 Organisation du test sur les décalages de faisceau LOC

THE ROLE OF THE AIRCRAFT MODEL IN AVIONIC SYSTEMS SIMULATION

J. D. BANNISTER and R. HICKS

British Aerospace - Aircraft Group

Kingston/Brough Division

Brough

North Humberside

SUMMARY

This paper discusses the relevance and use of the aircraft model in Avionics Systems Simulation. It is often required to study the interaction between elements of the Avionic System, the vehicle dynamics and the outside world and simulation provides a useful and cost-effective method.

Modelling of the outside world forms an essential part of any simulation and it is important to achieve a representation which is compatible with the objectives of the simulation. The outside world is considered to be that part of the simulation with which the system interacts to perform its function and a clear distinction should be made between the operational system and the outside world. An example is included to indicate the importance of making this distinction. In general, the simulation objectives determine whether the aircraft forms part of the outside world or part of the operational system.

The aircraft model is discussed in depth, to indicate the choice to be made in determining the level of complexity required to fulfil differing objectives. Aircraft models of different types are described. Some algorithms and solution techniques are presented along with an indication of the limitations inherent in the models.

Two contrasting simulations are then discussed in detail to show the significance of the aircraft model in relation to the avionic system simulation. The first example illustrates the use of an aircraft model in a GP computer simulation of the interception of invading aircraft. The second example discusses the aircraft model used in a pilot-in-the-loop real-time simulation of the avionics system for an attack aircraft. In both examples practical considerations are included such as processor requirements and simulation system architecture.

1. INTRODUCTION

The application of simulation to avionics systems has traditionally concentrated on the development of flight control systems and of flight deck simulators for the training of airline pilots. These applications are as important now as ever because of the use of active controls for flight control systems and because of the necessity to reduce pilot work-load particularly during the landing and take-off phases of flight in crowded airspace and during handling emergencies.

However, in recent years, increasing complexity of avionics systems coupled with the higher level of integration of systems and the increasing use of software instead of hardware to define the systems have led to much wider application of simulation. Some of the problems for which simulation techniques can be applied include :-

1) Flight deck and cockpit ergonomic design assessment

2) Avionic system integration and design verification

3) Software and hardware proving

4) Operational and effectiveness studies

5) Pilot training, both civil and military

Different levels of simulation are appropriate depending on the intended objectives e.g. weapon aiming studies require :

(i) General purpose computer simulation modelling of the scenario to test concepts and establish first order parameter values.

(ii) Fixed and moving base simulation to demonstrate pilot acceptibility.

(iii) System simulation to assist in the design and verification of the system architecture and to ensure integration with the total avionics system. Of particular value is the ability to design sub-system software and to demonstrate its compatability with the total system requirement.

When designing a simulation activity it is important to develop a clear understanding of the simulation objectives prior to the design. Experience has shown that failure to do this at the outset can result in large scale modifications being incurred. Any attempt to use a simulation designed around one set of objectives often leads to time consuming changes to satisfy a new set of objectives. However, over the life of a large scale simulation, objectives can change for a variety of reasons and unless adequate provision has been built into the original design a stage is reached when it is cost effective to start again. Perhaps

the most successful approach to achieving a simulator to satisfy a wide ranging set of objectives is the use of a modular construction of the software design with the interfaces between the components being as simple as possible and clearly specified.

2. OUTSIDE WORLD SIMULATION

It is often required to study the interaction between elements of an avionic system, the vehicle dynamics and the outside world and hence it is necessary to embed the system simulation within environmental models. The overall environmental simulation includes validated models of airframe, scenario geometry and atmosphere so that the system under test can receive realistic signals and produce results that can be accurately assessed for functional performance. Under differing circumstances the aircraft may form part of the system simulation or part of the outside world representation depending on the simulation objectives. The outside world has been assumed to be that part of the simulation with which the system to be studied interacts to perform its functions. A clear distinction should be made between the operational system and the outside world as the following example illustrates. This example is an extreme case but it serves to demonstrate the importance of establishing clear objectives at the outset and hence a satisfactory simulation design.

The simulation on a general purpose computer of a navigation technique for airborne vehicles is described by J. W. Lyons et al, 1975 (ref. 1). The navigation method uses correlation between terrain data as stored in the vehicle processors and terrain data as measured by the vehicle sensors (ranging laser and radio altimeter). For the simulation it is necessary to provide a representation of the terrain over which it is intended to fly and which is assumed to be part of the SYSTEM i.e. the terrain data stored in the vehicle processor. It is also necessary to provide a separate terrain representation as part of the OUTSIDE WORLD simulation and which is sampled by the vehicle sensors (Figure 1). Clearly it is essential that within the simulation the two requirements for a terrain representation are maintained conceptually distinct. This was achieved by setting up a basic terrain data base in the form of height ordinates at points on a rectangular grid with 100 metre spacing. This formed the basis of the outside world terrain representation with interpolation used to provide a smooth analogue representation. One of the objectives of the simulation was an investigation of the nature of terrain representation that would be appropriate for the vehicle processors to satisfy the navigation requirements. The method used a rectangular grid system with height ordinates stored at 150 metre intervals, although 200 metre intervals were found to be satisfactory. These height ordinates were derived from the interpolated outside world data base after it had been drawn in contour form. In this way the small errors incorporated in translating from the real world to the vehicle processor data, using standard surveying techniques, were included in the simulation. Hence, a clear distinction between the outside world simulation and the system simulation was achieved.

3. AIRCRAFT MODEL

As stated previously the aircraft may form part of the system simulation or part of the outside world representation. The examples to be discussed show its use as part of the outside world when evaluation of an aircraft cockpit is considered and as part of the system when the effectiveness of the total aircraft concept (with the avionics as part of that concept) is considered. While the simulation architecture is influenced by this distinction, the basic modelling of the aircraft flight dynamics is not. The model itself can be considered to be a module within the simulation. The model may be hosted within a general purpose processor which serves the total simulation or it may be separate from other elements of the simulation by adopting a federated processing system. The choice will depend on the nature of the simulation, the type of processor(s) available and other local constraints.

In designing an aircraft model to meet the needs of a particular application, the objectives of the simulation should first be assessed to determine the degree of complexity required. Aircraft models can vary from a simple moving point in space exhibiting properties such as radar cross-section, or infra-red signature up to a full representation in which the properties of the airframe, power-plant, systems, weapons and pilot are modelled as closely as possible. The simplest aircraft models are useful for, say, modelling of a total defence system in which the operation of fleets of aircraft are simulated. The simulation objectives could, for example, call for the primary effort to be expended on the siting and properties of the air defence radar environment, and only the macroscopic aspects of aircraft operations covering some hundreds of square kilometers are required to obtain valid results.

The most complete mathematical description of the aircraft is required in simulations involving direct, real-time, human interaction e.g. in the cockpit environment. Flight simulation of existing aircraft is already a commonplace reality, but the simulator may also be used as a design tool to establish acceptable pilot workload levels, explore handling characteristics of project aircraft, refine properties of active control systems and to design new cockpit layouts with head up displays, novel control mechanisms, switchable C.R.T. displays and digital data highway systems.

Before considering such applications in more detail, however, a brief indication is given of the mathematical description of the aircraft.

The model itself is based on the solution of a set of simultaneous non-linear differential equations which are used to describe the aircraft flight dynamics. These equations will be an approximation to the physical reality with the simulation requirements determining the nature of the approximations which are acceptable and the method of solving the equations.

When discussing the modelling of the aircraft in relation to its use in avionic simulations it is usually a requirement to embed a representation of the aircraft flight dynamics within a total control system. In this way the total aircraft response to pilot inputs is modelled. Then the aircraft flight dynamics are represented by a transfer function in a block diagram of the control system. The study of control systems and their representation in simulation is a vast topic and is not discussed in depth here. The intention is to indicate the method of obtaining the aircraft transfer function by defining the stability derivatives which relate the changes in the aerodynamic forces and moments acting on the aircraft.

It is firstly necessary to define an axis system and while a number of axis systems could be chosen it is conventional to define a system with its origin at the centre of gravity of the aircraft and its axes fixed either to the aircraft, in order to avoid moments of inertia which change with time - the Principal Body Axes - or to the instantaneous flight vector. This latter choice is the so-called Aerodynamic Body Axes, an orthogonal right-handed triad, in which the x axis lies along the instantaneous velocity vector with the y axis along the starboard wing and the z axis downward as seen by the pilot. It should be noted that in general the x axis is not aligned with the longitudinal axis of the aircraft but at some angle, α.

For small porturbation models an axis system is usually chosen which is initially aligned with the aerodynamic body axes at the start of the perturbation, and remaining fixed relative to the aircraft body during the perturbation. This axis system has been called "Stability Axes."

The equations of motion are obtained by applying Newtons Laws of motion and in general it is possible to make a number of simplifying assumptions although their validity will depend on the application;

1) It is usually safe to assume that the x and z axes lie in a plane of symmetry of the aircraft.

2) It can be assumed in general that for the short period of time that is relevant to a dynamic analysis the mass of the aircraft remains constant. Clearly this is not valid at and for a short time after weapon release and if the behaviour of the aircraft at this time is an important consideration this simplifying assumption cannot be made.

3) It is assumed for simulation purposes that the aircraft is a rigid body although again the validity of this assumption is dependent on the objectives of the simulation e.g. harmonisation of the radar and E.O. sensors with the HUD and inertial sensors requires to take account of structural bending.

4) It is assumed that the earth is an inertial reference with the atmosphere fixed with respect to the earth. This assumption is not valid for the analysis of inertial guidance systems but is for the analysis of control systems and greatly simplifies the final equations.

It can be shown that by applying Newtons Laws it requires six simultaneous non-linear equations of motion to completely describe the behaviour of a rigid aircraft. These equations give a full force and moment balance acting on the aircraft. Such equations can be found in classical literature but the form required for any application to aircraft model use depends upon the axis system which is chosen.

Examples of the two types of aircraft model follow. The first, is a small perturbation model which uses full aerodynamic stability derivatives but in two dimensions only, whilst the second is a full three dimensional model but using a simplified approach to the treatment of dynamic response of the aircraft.

In the simplest case, where the requirement is for a 2-dimensional, small perturbation, linear model, the equations of motion can be written in the form :-

$$\dot{u} = C_1 u + C_2 w + C_3 q + C_4 \theta$$

$$\dot{w} = C_5 u + C_6 w + C_7 q + C_8 (1 - \cos \theta)$$

$$\dot{q} = C_9 u + C_{10} w + C_{11} q + C_{12} \eta + C_{13} \dot{w}$$

where

$u, w \equiv$ pertubations in velocity in x, z axes

$q \equiv$ angular velocity about the y axis

$\theta \equiv$ a pertubation in pitch angle

$\eta \equiv$ elevator deflection

$C_1 = \frac{x_u}{\tau}$ $\quad C_2 = \frac{x_w}{\tau}$ $\quad C_3 = \frac{x_q V}{\mu}$ $\quad C_4 = \frac{-C_L}{2} \frac{V}{\tau} = -g$

$C_5 = \frac{z_u}{\tau}$ $\quad C_6 = \frac{z_w}{\tau}$ $\quad C_7 = (1 + \frac{z_q}{\mu}) V$ $\quad C_8 = \frac{-C_L}{2} \frac{V}{\tau} = -g$

$C_9 = \frac{\mu m_u}{V I_B \tau^2}$ $\quad C_{10} = \frac{\mu m_w}{V I_B \tau^2}$ $\quad C_{11} = \frac{m_q}{I_B \tau}$ $\quad C_{12} = \frac{\mu m_\eta}{I_B \tau^2}$

$C_{13} = \frac{\mu m_{\dot{w}}}{V I_B \tau}$

where x_u, x_w, x_q ≡ forward force derivatives

z_u, z_w, z_q ≡ normal force derivatives

m_u, m_w, m_q ≡ pitching moment derivatives

m_η ≡ pitching moment derivative due to elevator deflection

τ ≡ "non-dimensional" time $\frac{W}{g\rho VS}$

V ≡ equilibrium aircraft velocity

μ ≡ $\frac{W}{g\rho S l_t}$ = aircraft density ratio

g ≡ acceleration due to gravity

C_L ≡ Lift coefficient

i_B ≡ $\frac{Bg}{W l_t^2}$

B ≡ moment of inertia about y- axis

l_t ≡ tail moment arm

S ≡ aircraft reference wing area

W ≡ current aircraft weight

The assumptions made in arriving at these equations are :-

(i) disturbances are small, about the equilibrium condition

(ii) the product of variations can therefore be neglected compared to the variations

(iii) small angle assumptions are valid for angles between the equilibrium and disturbed axes

(iv) the x axis is aligned with the velocity vector while the aircraft is in equilibrium flight

These equations have been used in the simulation of a simple terrain following system where the objective was the study of the terrain following control system in the pitch plane. In such a simulation the effects of turning flight have to be considered independently.

For many simulations a small perturbation model will not be adequate. It will be necessary to simulate the full aerodynamic effects and engine performance effects. Examples of such simulations are described in Sections 4 and 5. In particular the aircraft differential equations used with the close combat model are given below.

This model uses the Euler system to define the angles in space, and makes use of both the Principal Body Axis (P.B.A.) and the Aerodynamic Body Axis (A.B.A.) systems in order to define the state of the aircraft fully.

$$\dot{V} = g\left(\frac{T\cos\alpha - D}{W} - \sin\Theta\right)$$

$$\dot{p} = K_1(\phi_D - \phi) - K_2\dot{\phi}$$

$$\dot{\alpha} = q - q_w$$

$$\dot{\theta} = q\cos\phi - r\sin\phi$$

$$\dot{\phi} = \tan\theta\,(r\cos\phi + q\sin\phi) + p$$

$$\dot{\Theta} = q_w\cos\Phi - r_w\sin\Phi$$

$$\dot{\Phi} = \dot{\Psi}\sin\Theta + p_w$$

$$\dot{\Psi} = \frac{q_w\sin\Phi + r_w\cos\Phi}{\cos\Theta}$$

$$\dot{X} = V \cos \Theta \cos \Psi$$

$$\dot{Y} = V \cos \Theta \sin \Psi$$

$$\dot{h} = V \sin \Theta$$

$$\dot{q} = K_3 (q_D - q) \cos^2 \alpha$$

$$\dot{w} = T (- sfc)$$

where

$$r = \frac{g \cos \theta \cos \phi}{V \cos \alpha}$$

$$p_w = p \cos \alpha + r \sin \alpha$$

$$r_w = r \cos \alpha - p \sin \alpha$$

$$q_w = g \frac{(T \sin \alpha + L - W \cos \Theta \cos \Phi)}{W.\ V}$$

$$L = \tfrac{1}{2} \rho V^2 S C_L$$

$$L\ max = \tfrac{1}{2} \rho V^2 S C_{L\ max}$$

$$D = \tfrac{1}{2} \rho V^2 S C_D$$

where $T \equiv$ engine thrust at current throttle setting

$V \equiv$ velocity

$p \equiv$ roll rate

$q \equiv$ pitch rate

$r \equiv$ yaw rate

$\alpha \equiv$ angle of incidence

$\theta, \phi, \psi \equiv$ angle of pitch, bank and azimuth in principal body axes

$\Theta, \Phi, \Psi \equiv$ angle of pitch, bank and azimuth in aerodynamic body axes

$X, Y, h \equiv$ position in earth axes

$W \equiv$ aircraft weight

subscript 'w' denotes variables in aerodynamic body axes.

These equations make use of the following assumptions :-

(i) There is no appreciable sideslip

(ii) Values of K_1, K_2 and K_3 can be specified for all Mach numbers, altitudes and 'g' loadings

(iii) The functions :

T - engine thrust

D - aircraft drag (or C_D in coefficient form)

sfc - engine specific fuel consumption

C_L - lift coefficient

C_L max - maximum usable lift coefficient

can be specified in tabular form with sufficient accuracy to give a good representation of the vehicle properties. These functions are allowed to vary with the following independent variables as required: Mach number, Altitude, α , C_L , and Engine throttle setting.

A similar set of equations has been used with the cockpit simulation. A matrix approach was chosen for the description of the aircraft's aerodynamic characteristics. One of the important but time-consuming tasks when setting up a simulation is in describing the aircraft parameters in a convenient form and since the extensive programming existed the inevitable overhead associated with the matrix approach was accepted. The method produced a full non-linear model which combined the convenience of a matrix description of the aerodynamics with the efficiency with which a conventional numerical integration can present non-linear phenomena. This was achieved by representing the aircraft rigid body dynamics using a conventional numerical integration technique, thereby reducing the frequency with which the system description matrix needed re-evaluating. Figure 2 shows the program structure.

SOLUTION OF THE AIRCRAFT EQUATIONS

In general, the requirement is to solve the set of first order simultaneous differential equations which describe the six degrees of freedom of the aircraft motion. Ideally a method of solution is sought which converges rapidly, requires a minimum of computer storage space, is simple to execute (i.e. does not require the computation of higher derivatives) and provides readily obtainable estimates of the errors involved. While there are a number of possible methods, there are none available which satisfy all these desirable characteristics. The most commonly used approach is the use of one of the various Runge-Kutta methods. They all have the distinguishing properties that

1. they are one step methods i.e. the solution is obtained by using the values of the variables at the previous point only. Hence they can be considered as self starting techniques.

2. they do not require the evaluation of any of the derivatives, but only the functions themselves. However, it is necessary to evaluate the functions for more than one value within the step width. Essentially this is the trade-off involved in avoiding the evaluation of higher derivatives.

One of the major disadvantages of the Runge-Kutta methods is the lack of a simple means for estimating the errors. Without some measure of the truncation error it is difficult to choose a suitable step size over which to carry out the integration. An estimate of the truncation errors can be obtained with additional computing but in practice the step width is often chosen on a trial-and-error basis and constrained by the computing time available to achieve a solution.

The most convenient Runge-Kutta method for this application has been found to be a fourth order method. The equations are solved over the chosen time interval, then using half the interval and the solution checked for convergence. If adequate convergence is not achieved the interval is again halved and the equations solved. The process is repeated until adequate convergence is achieved or computing time for the operation is exhausted,

4. INTERCEPTION SIMULATION

As an illustration of the selection and use of appropriate aircraft models for simulation, two contrasting examples have been chosen. The first of these illustrates the use of aircraft models with different degrees of complexity, and also it illustrates how the definition of outside world varies with the definition of the objectives.

The problem is to predict the efficiency of a defence system when faced with an opposing invading force entering the airspace which is to be defended. A full simulation using actual equipment is often the subject of N.A.T.O. exercises, and clearly an extremely expensive undertaking.

Further, a full digital simulation of a defence system as a whole is expensive - even if a large dedicated computer system could be made available to run such a simulation. A more cost effective approach is to split the simulation into manageable portions, analyse the critical elements in any particular portion, and then reconstitute the interception from the constituent parts. The aircraft model is tailored to the most appropriate form for each portion of the simulation.

The simulation of an interception can be said to cover three phases :

(i) The acquisition of the enemy, followed by the take-off (if not on C.A.P.), climb/descend to height and acceleration.

(ii) The vectoring phase

(iii) The engagement.

The first phase tends to be a separate problem, and gives the initial distance covered and fuel used in gaining the desired height and speed (Reference 3).

In phase two, the aircraft tends to be at some cruise, or steady state, operating at moderate 'g' levels. It is the vectoring aspects which are under close scrutiny. Accordingly we can use an aircraft model which is simplified to use only parameters affecting performance. These parameters, generally supplied as a function of speed and altitude, include fuel consumption, maximum turn rates and maximum acceleration rates. It is the acquisition radar systems and the communications to the interceptors, in an E.C.M. environment, which are under investigation whether they are ground based (G.C.I.), airborne (A.E.W. or A.W.A.C.S.) or interceptor mounted (C.A.P.). The simulation is particularly aimed at finding out how the errors in the acquisition systems affect the success or otherwise of the interception as a whole. These errors, generally in some given deterministic or stochastic form occupy the major effort in the simulation, and it can be seen that the aircraft model for both target and interceptor can be quite simple without affecting the validity of the model.

Results of a typical simulation are shown in Figure (3), which shows the interception of an intruder which can choose to weave or to press on with the attack by flying straight and level. The figure shows a time history of the interception from the initial take-off to the final kill, giving major parameters (fuel, speed, altitude) at key points of the trajectory.

The vectoring phase of the engagement can be said to end, either on release of long/medium range missiles, or at the start of the engagement, which can be close combat, if the target aircraft have that inclination or denial-of-escape combat should the target attempt to disengage. The former requires an extensive missile program for continuation, whereas the engagement requires a model with full description of the aircraft. The requirements for the aircraft model in close combat will be considered in more detail. Denial-of-escape simulation needs similar aircraft modelling, but with the emphasis on missile parameters rather than aircraft parameters. The modelling of missile flight and kill probabilities merits considerable

attention in its own right.

Here the emphasis is on the aircraft model. The complexity demanded by close-combat simulation is such that the motion of the aircraft in space should be very fully represented, and the simulation incorporates a mathematical representation of aerodynamic properties, engine capabilities as well as airborne interception radar, pilot and aircraft 'g' tolerance and weapon kinematic and acquisition boundaries.

Figure (4), shows the aircraft model part of a close combat simulation program. The model operates by integrating the non-linear differential equations over a finite time interval using the classical Runge-Kutta process.

The information available from this process will include those variables in Section 3 and in each case, their derivatives with respect to time will also be available for use in other modules of the program.

The tactics routines operating to given decision rules determine the acceleration components input to the aircraft model. The response is determined by the aircraft model, which also applies limits of aircraft and pilot performance when necessary.

There are also the basic properties of the aircraft and weapon system, supplied as data. These include :

Full engine performance, thrust and fuel consumption

Drag polars for the aircraft

Lift characteristics (including limiting values)

Structure limits.

These are supplied in tabular form, with the variation with Mach number and altitude predetermined.

Pilot 'g' tolerance is also modelled as a function of time.

The sensors aboard the aircraft - including the pilot's own eyes - supply the information to the tactics modules which in turn drive the aircraft model. Hence they should be simulated adequately, so that the information used by each aircraft in the combat - which may include the simulation of errors in the system - is representative of that used for tactical decisions and reflects air force practice. (In fact the tactics used often present the principal problems to the modeller). This information can include the following parameters, which may be used with or without error simulation : Range, Look Angle, Aspect Angle, Sight Line Spin.

Again, in each case, derivatives with respect to time are available. Variables may only be used, of course, when it is considered they are available to the pilot in following the decision rules.

In a similar way, the flight of a missile or shell can be modelled to complete the interception simulation at the kill (or miss!) in which case the missile on-board E-O equipment may be modelled to a similar level.

The total simulation operates as a 'M' against 'N' contest, in which 'M' aircraft of one side 'fly' against 'N' aircraft of the other side, where both 'M' and 'N' are necessarily small numbers, less than 10, say. Each of the aircraft makes a 'move', i.e. makes a tactical decision on how to move based on his knowledge of the state of combat, and is moved accordingly by the numerical integration process over a single time step. All aircraft move to complete one round, and the process is repeated until a time limit, or winning side appears. This is shown in Figure (5).

The decision rules built into close combat models are taken from a consensus of opinion of service pilots, projection of trends and experience from using the model.

Full input data for the aircraft as described previously are required to run such a simulation, with the addition of a complete description of initial starting geometries, and data to define the decision rules.

The weapon data are supplied as a table of launch success zones (L.S.Z.) again as a function of Mach number and altitude, and also target 'g'. (It will be noted, however, that a weapon launched within a L.S.Z. need not necessarily be successful, due to target evasive manoeuvre during the flight time of the missile.) Acquisition zones are treated similarily. Gun capabilities are also modelled. Single shot kill probabilities are assigned to each type of weapon fitted. This factor is crucially important for deciding when a kill has occurred and hence when a combatant is removed from the engagement.

Figure (6) shows a plan view of a typical engagement.

To fully simulate an interception, separate programs covering all phases may be put together sequentially to obtain full interception simulation as shown in Figure 3. This gives a means of studying the degree of success of the defence system in intercepting intruders, and can help to high-light where there are particular deficiencies in performance.

The interception programs can help both the aircraft manufacturer and the defence scientist to tailor future aircraft to the needs of the defence system given a predicted level of threat. Parametric variations of important variables - in aircraft, weapons or avionic systems, for example - are possible,enabling the programs to be used as a design tool.

5. COCKPIT SIMULATION

This simulation illustrates the most complex application of the aircraft model, with the inclusion of

a pilot in the loop.

It concerns the design of a single seat fighter cockpit. Here the requirement is to layout the cockpit facilities in such a way that the pilot can fulfil the mission tasks. This requires that the pilot is provided with just the information and controls that are necessary to enable him to carry out the tasks required of him. In addition it is required to test the concepts developed and to demonstrate pilot acceptability. Where new facilities or functions are provided or where the cockpit departs radically from current aircraft layouts, it will be necessary at a later date to familiarise operational pilots with the concepts and to provide a measure of initial training. At the design stage it will be necessary also to demonstrate the engineering feasibility of the proposed arrangement and the integration of the cockpit with the rest of the operational and flight control systems, making due allowance for the occurrence of failures and errors within the cockpit or systems.

These are among the reasons why it is virtually essential during the development phase of the cockpit to use mockups, space models, simulators and system rigs.

Traditionally the cockpit has been designed very much on an ad hoc basis with the basic flight control parameters being presented in front of the pilot in the conventional configuration of electromechanical instruments. Other displays and controls have been positioned depending on space available, the designers personal preference and "we've always done it that way." Controls and switches have been associated with specific equipments with little attempt made to integrate or rationalise related functions. The result can best be described as an "ergonomic slum." The addition of further systems or modifications during the life of the aircraft has merely added to the chaos and the overcrowding.

This "design" process may have been adequate during the early years of aviation when the facilities that could be provided to assist the pilot were limited and when aircraft speeds were more modest and therefore the pilot had more time to perform the mission tasks. However, it is clear that this process is thoroughly inadequate for the design of a modern cockpit. Technology allows us to present the pilot with far more information and hence mission tasks have become far more demanding. The requirement is for faster and more highly manoeuvreable aircraft. Hence the pilot has less time to carry out the required tasks. Cockpit design therefore becomes a much more exact science (Reference 4) demanding the adoption of established ergonomic principles during the design process and the use of basic ergonomic test and measurement procedures during development. Only then can a near optimum presentation of information and control facilities be provided in the limited space available and laid out in such a way as to make the pilot's work load tolerable.

During the cockpit development therefore, it is useful to check the basic configuration by constructing a space model and by introducing into the mockup basic pilot tasks such as air-to-air target tracking using a functioning flight control stick while requiring the pilot to perform normal in-flight switching tasks. A configuration which allows these tasks to be addressed is shown in Figure 7. Here the aircraft model is hosted on an analogue computer which also serves to drive the target model. The secondary task is driven from a small micro-processor unit. The advantage of using an analogue computer to host the aircraft model is in eliminating problems in achieving real time response from the model. However, much flexibility is lost and it proved necessary to use a simple linear 3-D model to represent the aircraft because of the difficulty of updating the aircraft derivatives during operation. During this process a first order definition of the facilities which should be provided to the pilot is achieved by eliminating any that are not directly relevant to the pilot's decision making process or those that would certainly overload the pilot. Hence we are in the situation where it is necessary to be highly selective in the facilities provided and in the manner of presentation. If the overall aircraft design is to be successful it has become necessary to design the operational systems from the pilot and his environment outwards rather than by choosing the facilities which technology allows and hoping that the pilot will cope with the highly sophisticated but ergonomically impossible system.

The next step in the development is the construction of a fully functioning cockpit with meaningful outside world representation to allow ergonomic measurement to be made while providing the pilot with representative tasks to perform. At this stage it is not possible to eliminate entirely subjective opinion but by introducing a large number of pilots to the concept in a semi-realistic environment it is possible to obtain a satisfactory pilot assessment. In addition the cockpit simulator provides the basic facilities necessary to carry out tests and measurements. Obviously the degree of realism provided in the simulation at this stage should be sufficient to tempt the pilots to treat the assessment process seriously, while sufficient flexibility should be retained to allow modifications and adjustments to be made reasonably painlessly. Clearly this stage of simulation requires the design and programming of a basic aircraft flight control system and aircraft model to represent the aircraft, elements of the avionic system sufficient to cause the displays to react in a representative manner in response to switching actions etc., and an outside world representation to provide the pilot with meaningful tasks against which to assess the cockpit concept. A possible advanced cockpit layout is shown in Figure 8. The major features shown include an articulating seat and side arm flight controller, electronic C.R.T. displays and switches for ease of accessibility along the side consoles. (Reference 2).

In setting up the simulation system the aircraft model can be chosen to suit the assessment objectives. However, since the requirements will usually demand a fair degree of realism a full 6 - degree of freedom non-linear model should be adopted. Then to achieve the required real-time operation it is necessary to consider carefully the speed of operation of the host computer. The major time consuming element is the updating of the aircraft derivatives as the flight conditions change. The choice rests between updating all the derivatives on a periodic basis or checking the sensitivity of each derivative to change in aircraft operating condition and updating only when the derivatives stray from the allowable bounds, checks being carried out each program cycle. It is important to avoid significant step changes in the derivatives which give uneven feel to the pilot. For reasons of simplicity the former method is desirable where sufficient time is available. It has the disadvantage of being extravagant in time during steady flight conditions since update of the derivatives has to be carried out at a rate which allows violent aircraft manoeuvres to appear realistic to the pilot. Experience has shown that when time is at a premium a suitable compromise is to update the sensitive derivatives on a periodic basis and to check the others at a less frequent interval.

For the cockpit simulation previously described the configuration used is shown in Figure 9. This shows the use of dedicated micro-computers to carry out basic system simulation and cockpit interfacing functions.

Further development phases involve :-

(i) The use of a moving base simulator in which a further stage of realism is introduced.

(ii) The incorporation of the cockpit into a system development rig to demonstrate the integrity of the full system on the ground.

(iii) An airborne cockpit demonstrator to provide the final confidence check and (hopefully) minor adjustments before the cockpit concept is incorporated in the design for a production aircraft.

6. CONCLUSIONS

The paper has discussed the basic representation of aircraft flight dynamics for use with avionic simulations. No attempt has been made to address the separate issue of flight control system simulation. Examples have been chosen to illustrate the use of varying levels of complexity of aircraft model and an indication given of the simplifications possible for different levels. Clearly the cockpit simulation with a pilot in the loop, requires the most complex and accurate representation of the aircraft.

It has been shown that in general, the simulation objectives indicate the model to be chosen.

7. ACKNOWLEDGEMENTS

The authors acknowledge the help given by colleagues at British Aerospace during the preparation of this paper. Permission to publish the paper is by courtesy of British Aerospace. The opinions expressed however, are entirely those of the authors.

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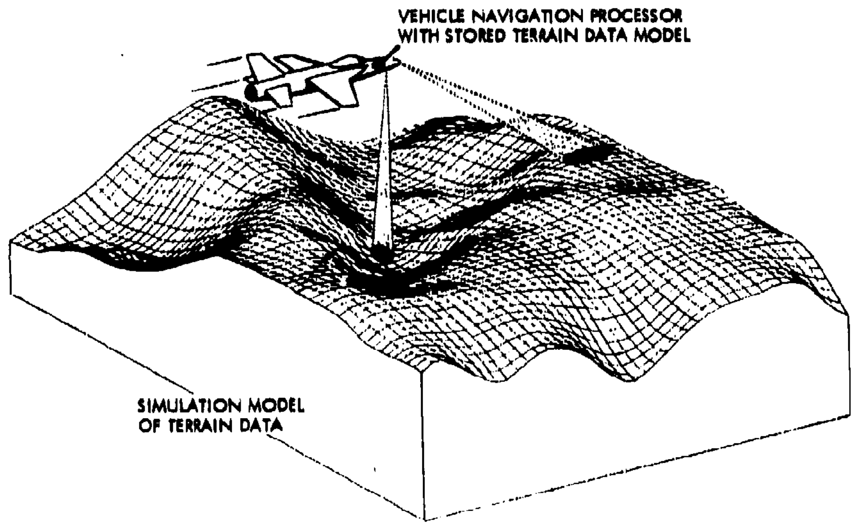

Figure 1 Navigation Simulation

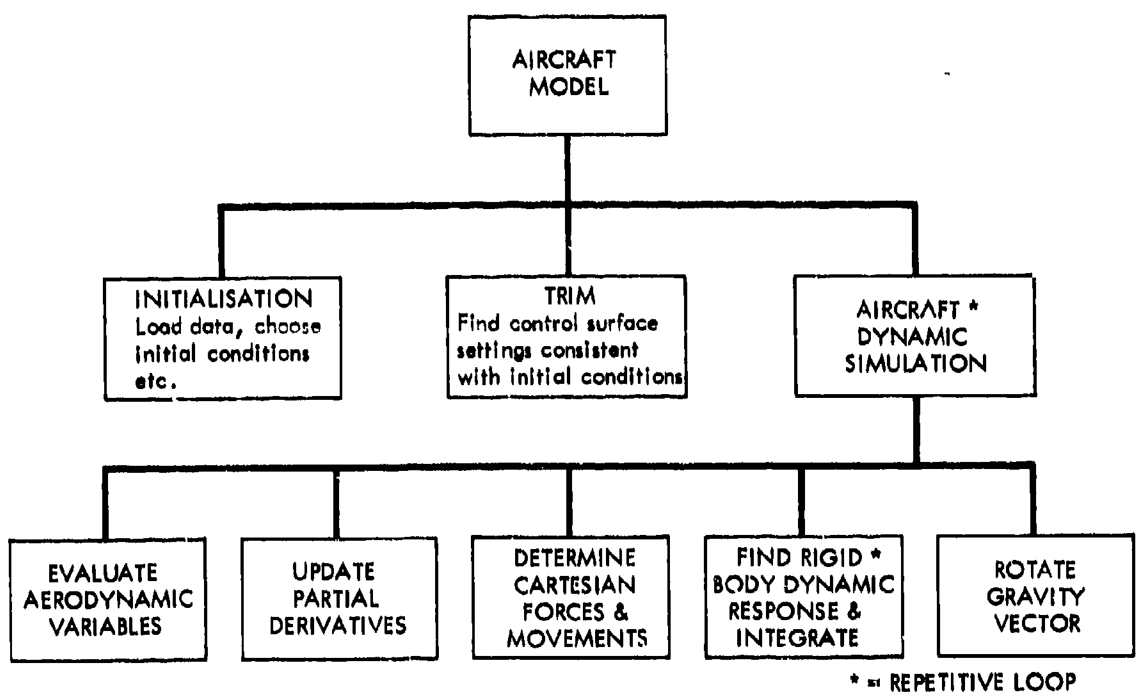

Figure 2 Program Structure for Aircraft Model

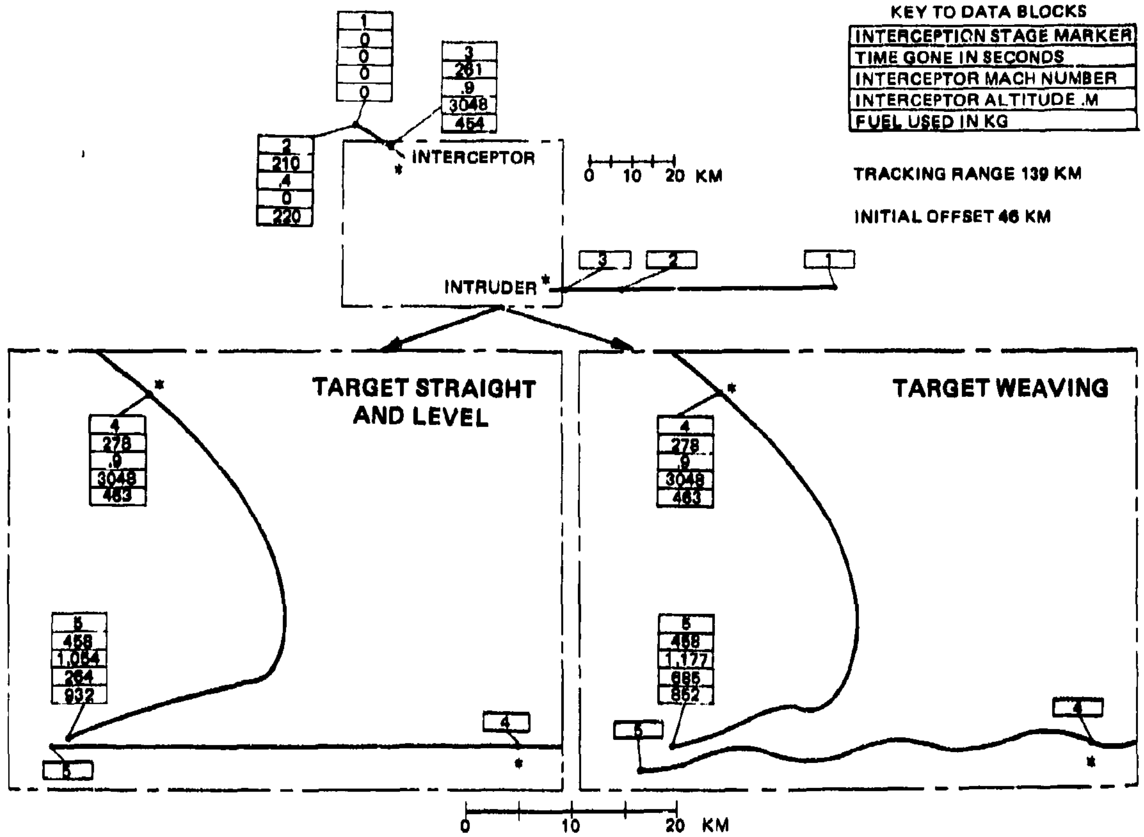

Figure 3 Interception Simulation Results

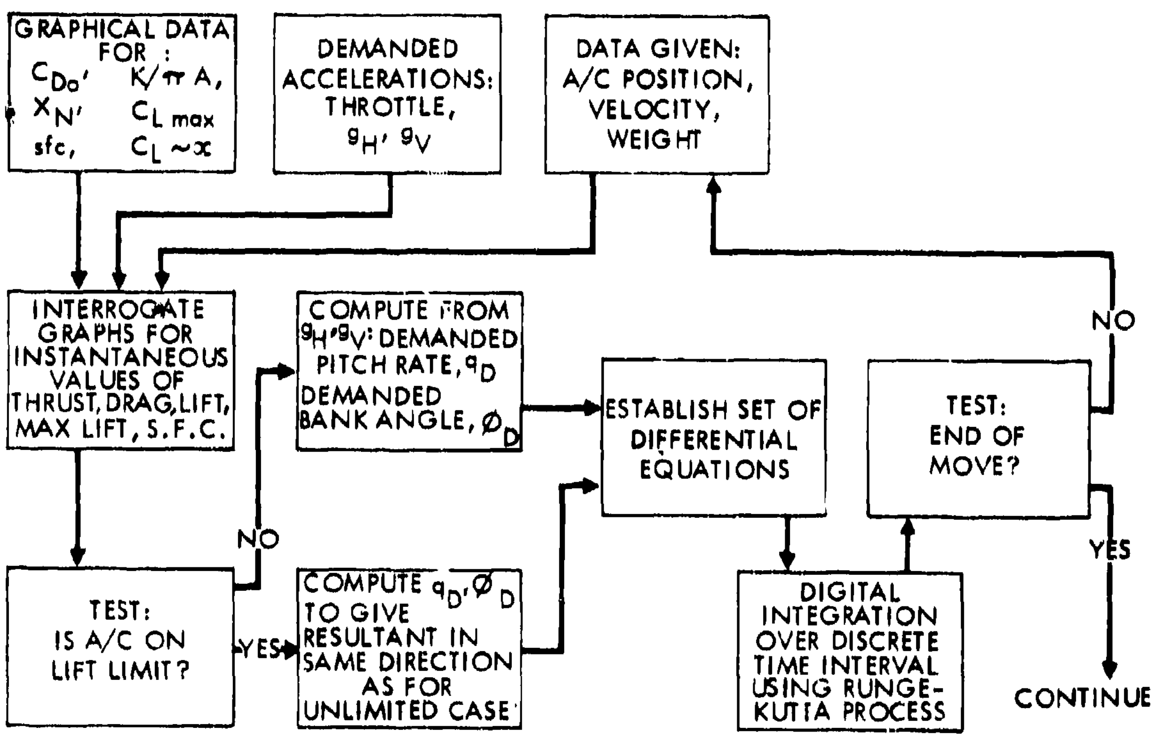

Figure 4 Aircraft Model Diagrammatic Representation

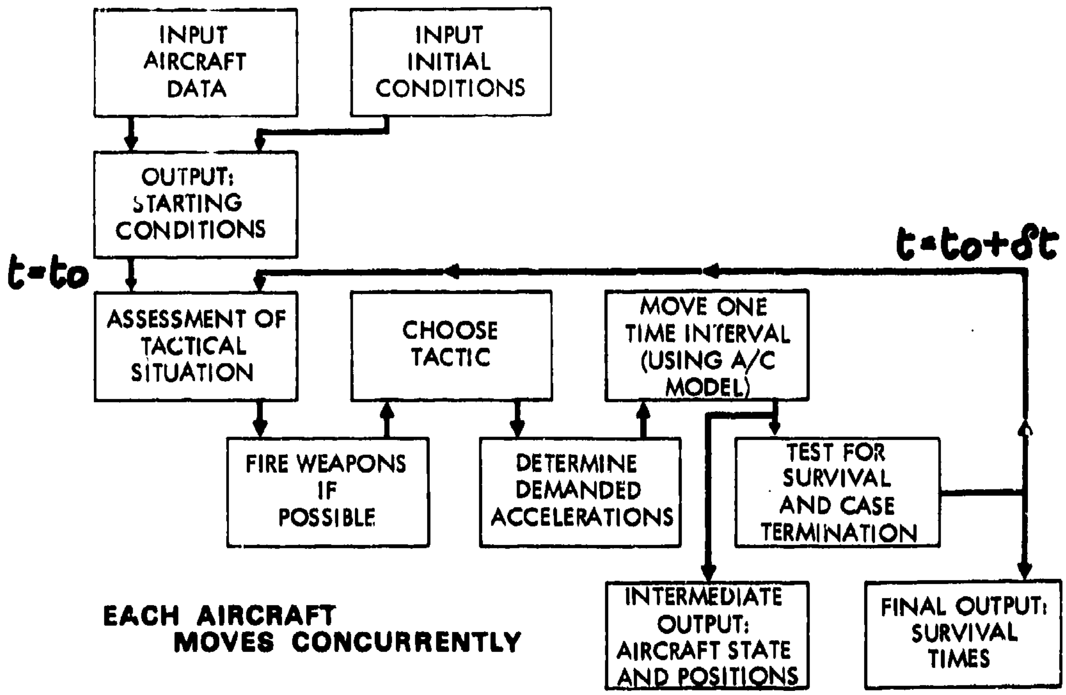

Figure 5 Flow Diagram of Combat Simulation

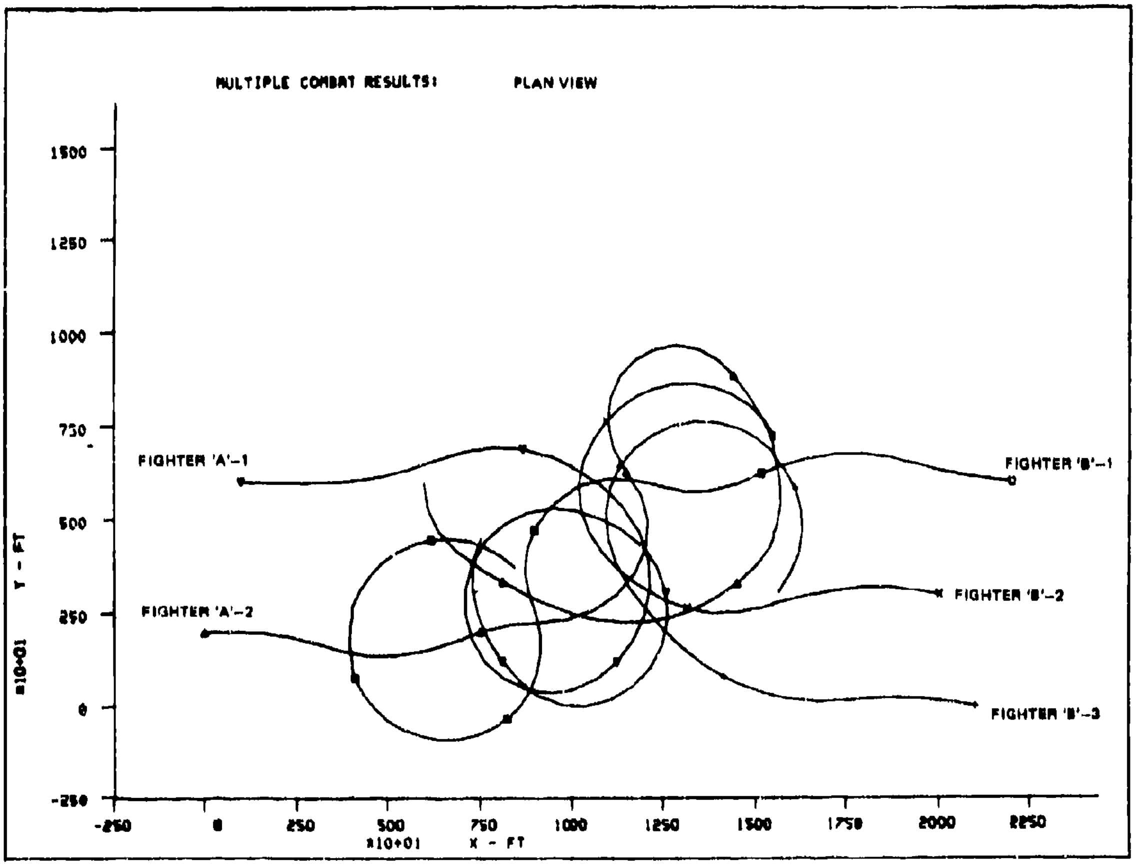

Figure 6 Multiple Combat Results

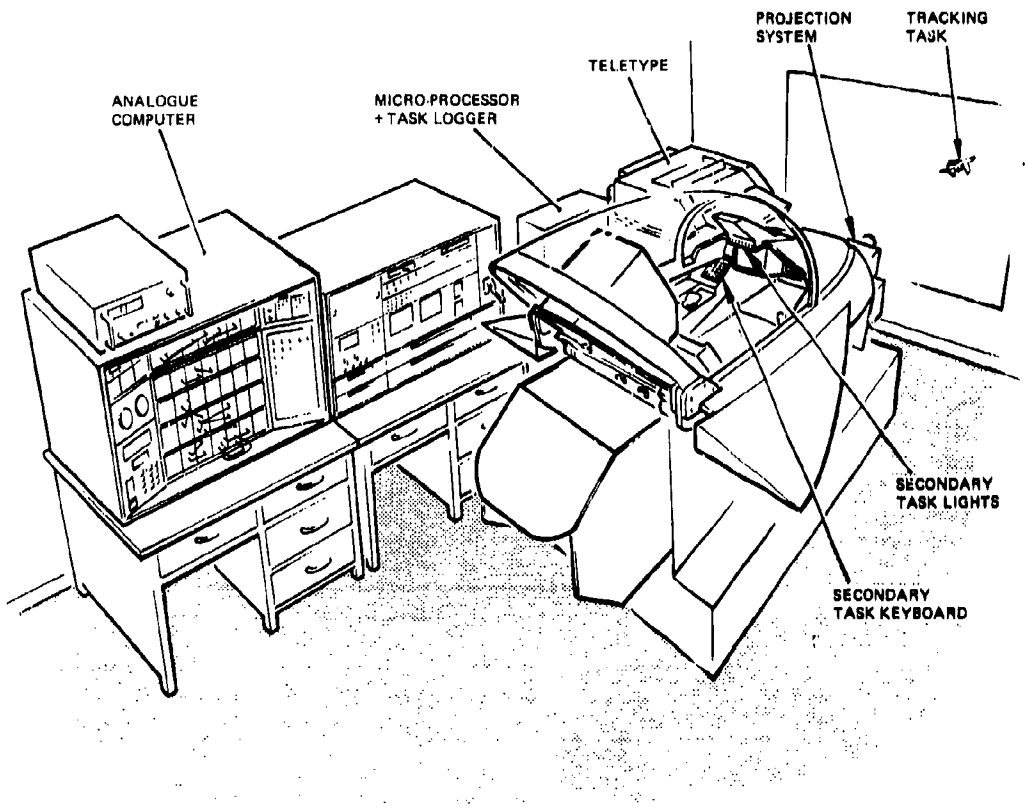

Figure 7 Advanced Cockpit Simulator (Analogue)

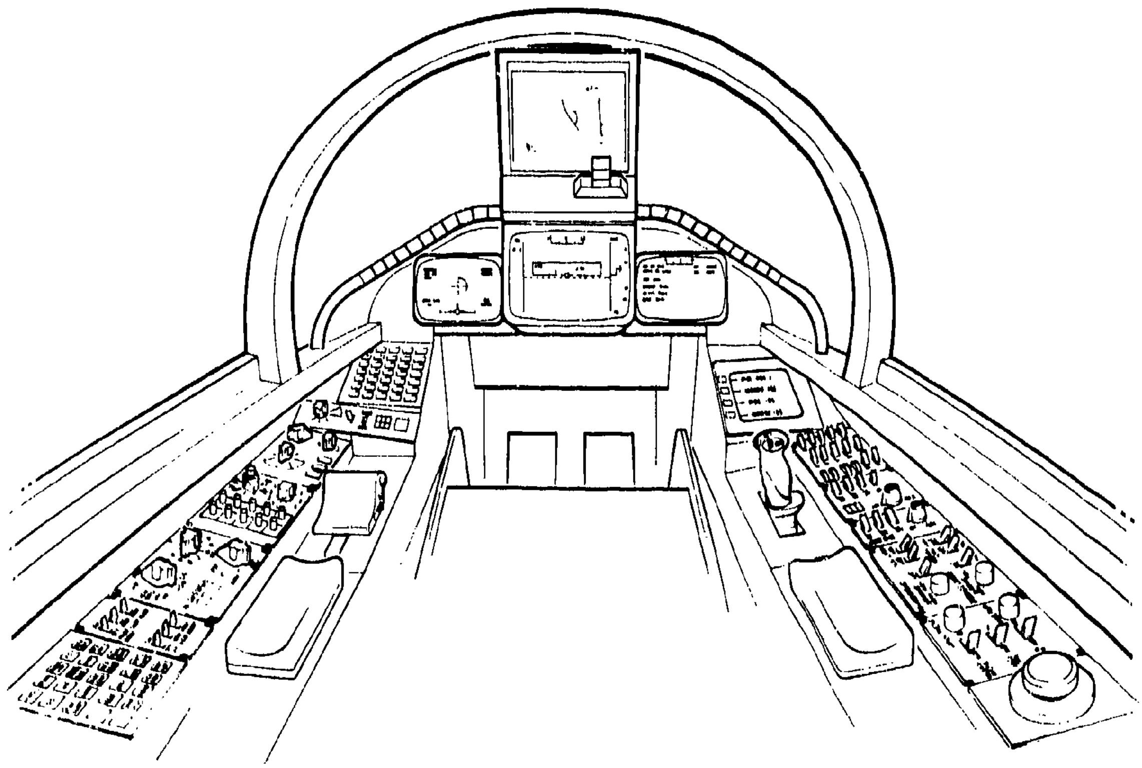

Figure 8 Advanced Cockpit Layout

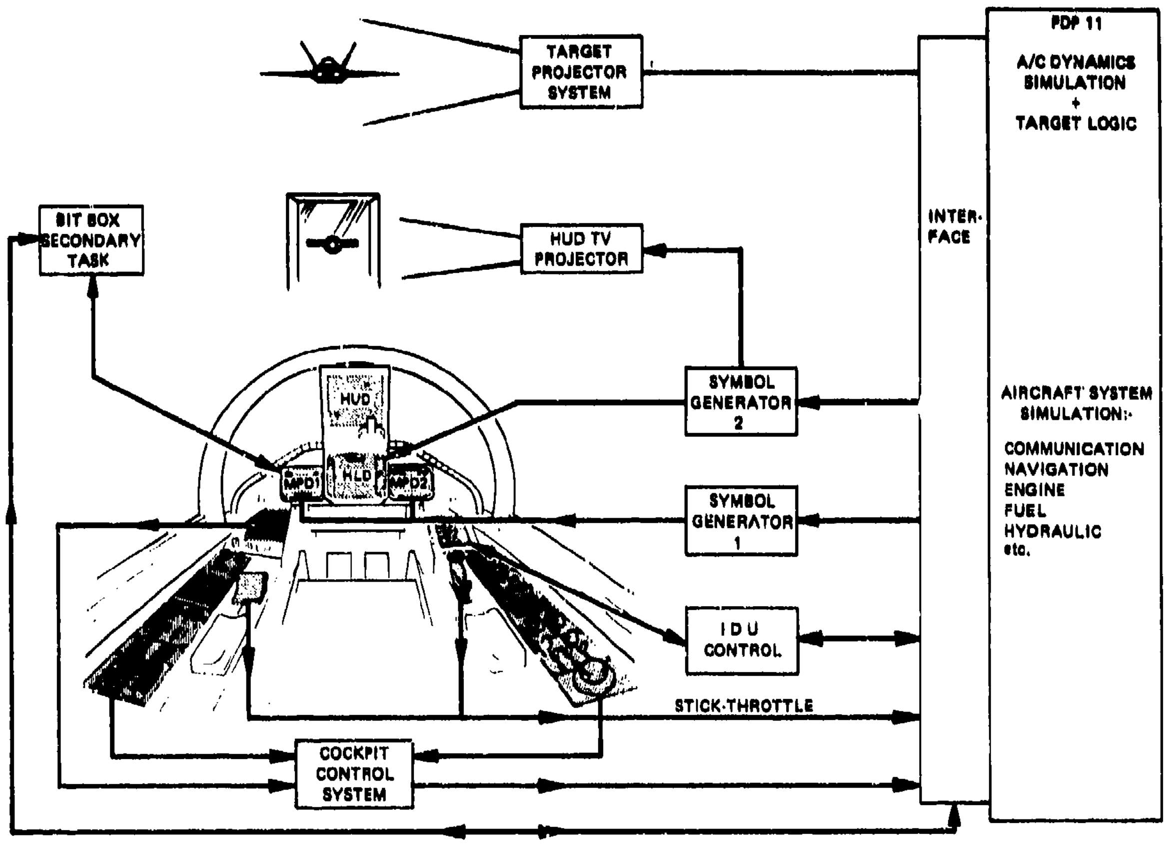

Figure 9 Advanced Cockpit Mechanisation (Digital)

AVIONICS EVALUATION PROGRAM:

SIMULATION MODELS FOR THE EFFECTIVENESS ANALYSIS OF AVIONICS

Mr David Welp
Battelle Columbus Laboratories
(Now With Texas Instruments)

Capt Ken Almquist
Capt Larry Rainey (editor)

AFAL/AAA-3, Wright-Patterson AFB, OH 45433

SUMMARY

In the present inflationary economic environment there exists a highly constrained defense budget which severely limits the acquisition of new, higher performance Air Force weapon systems. Therefore, system developers cannot pursue an independent, open-ended search for maximum performance. New weapon system developments must now be justified on the basis of improved cost-effectiveness for the entire system over its projected lifetime. A solution to this task is found in the Avionics Evaluation Program (AEP) which is a library of seven detailed avionics performance assessment models all driven by a common interactive software package. The AEP provides an efficient means for performing trade-off analyses among cost, reliability, maintainability, and performance of avionic configurations. The program was designed to be flexible and easy to use with emphasis on realistic consideration of the operational environment and the generation of useful data.

1. INTRODUCTION

The Avionics Evaluation Program is a collection of avionics performance assessment models developed for the use of the Air Force Avionics Laboratory by Battelle's Columbus Laboratories. Development of the AEP was motivated by the need for a convenient and systematic method of assessing the performance of avionic systems in the mission environment.

The initial model development, begun in 1969, concentrated primarily on a mission analysis model for the tactical air-to-ground role. Subsequently, models for more detailed analysis of target acquisition, weapon delivery, tactical data link communications, and anti-aircraft survivability were added to the AEP interactive framework. In 1975, an air-to-air version of the mission analysis program was developed. Two separate supporting programs have been added for deterministic analysis of air-to-air combat encounters.

The AEP has been designed to be flexible and easy to use with emphasis on the realistic consideration of the operational environment and the generation of useful data. The modular structure of the AEP allows independent use of the supporting models as well as the use of the supporting models to generate data for the mission analysis program. The modular structure also facilitates the addition of additional models and the modification of the models. In 1973, the AEP was implemented in a conversational interactive mode to make the collection of programs directly accessible to analysts with minimal computer programming experience. The resulting sophisticated software package has proven to be a valuable asset in making the models available to a wide spectrum of users in government and industry.

2. Air-To-Ground Mission Analysis Program (AEP)

The AEP air-to-ground mission analysis program evaluates performance of an airborne weapon system on a mission which may involve multiple aircraft and multiple targets. The program evaluates the operation of a flight of up to four aircraft for a specified number of days of operation, including the ground turnaround process. Monte Carlo techniques are applied to reliability data for the defined aircraft equipment throughout the mission to determine which subsystem modes are functioning--resorting to backup modes and mission aborts as required. Target location uncertainties and navigation system performance parameters are combined to define the actual flight path relative to the true target location. The sensor ground swath for the search pattern is then compared to the true target location to determine if the target passes through the sensor ground area coverage. Probabilities of detection, target kill and aircraft survival are sampled to determine which mission phases are successfully completed. The model utilizes the best mode still available for each function at the time it is to be performed.

The following steps are required to set up a problem:

(1) The mission must be defined in terms of the target, threat, and weapons.

(2) The flight profile is defined using waypoints to describe flight segments.

(3) A suite of hardware (black boxes) describing the complete aircraft is itemized. Reliability and maintenance data are provided for each black box.

(4) The required mission functions are selected (typical functions include navigation, navigation update, target acquisition, weapon delivery, survivability, communications, refueling, etc.).

(5) For each function, the primary and backup modes of operation must be defined. A mode is defined by specifying the performance capability (if applicable) and assigning the hardware black boxes required to operate in that mode.

The output is composed of statistics describing the mission events for the selected number of Monte Carlo trials. The outputs include targets destroyed, mission aborts, aircraft losses, targets detected, average number of attack passes per target, mission costs, and a statistical summary of the ground servicing and

maintenance activities.

3. Target Acquisition

A comprehensive set of target acquisition models covering the unaided operator, TV, FLIR, radar, and photographic cameras are available in the AEP interactive system. The models, grouped under the acronym ALSPM (Avionics Laboratory Sensor Performance Model), were originally developed for the Aeronautical Systems Division at Wright-Patterson AFB, Ohio by Honeywell, Inc. These models were initially intended for analysis of reconnaissance sensors but are equally applicable to real time target acquisition.

In addition to the computer models, there is an associated library of data available from which the user can select descriptions of the target, scene, and sensor. The target is characterized by type (isolated element, linear array, or area target), dimensions, reflectivity, emissivity, or radar cross section, as appropriate to the sensor spectrum. Similar data are required for the background in the immediate vicinity of the target. Scene data include characterizations of the weather and local terrain. The weather data are used to compute transmissivity and backscatter functions. The terrain data are used to compute the likelihood that line of sight exists.

Sensor data include characterizations of lenses, filters, photosurfaces, electronics, displays, film, radar receivers, etc. The data are used to compute the signal-to-noise ratio, target-to-background contrast, and resolution as viewed on a display (or directly viewed by an observer).

The models compute the likelihood that an observer can detect the presence of a target-like object(s), recognize the class of target (e.g., wheeled vehicle, tracked vehicle, building), and identify the target (e.g., T-62 tank, fuel truck). Detection probability is based on target size and contrast, signal-to-noise ratio, time in view, and density of confusing objects. The human factors model allows selection of three detection probability algorithms--the Stathacopoulos Model, the Williams Model, or the Rosell and Wilson Model.

ALSPM is continually being updated to achieve more realistic assessment of target acquisition capabilities. The FLIR and TV models have recently been updated to reflect the current approach to sensor performance assessment and the latest in experimental data. This update includes transition to a modulation transfer function analysis of the system components.

4. Weapon Delivery

The weapon delivery analysis routine is a program for determining the distribution of impact errors for a weapon system utilizing unguided, unpowered bombs. The model is a single program providing for the evaluation of most existing and future weapon delivery systems. The program is convenient to use with only a basic understanding of how a specific weapon delivery system operates.

The routine can be operated in three modes:

(1) The user can supply a weapon release algorithm in the form of a FORTRAN subroutine under defined guidelines.

(2) The user can supply equations which transform the sensor measurements into rectangular coordinate estimates of position, velocity, and wind relative to the target. Thirteen system implementations using this technique are presently stored in the program.

(3) The third mode requires a user-supplied FORTRAN subroutine duplicating the weapon release algorithm as in Mode 1. This mode, however, applies to systems which employ filtering and for which the user chooses to specify the sensor errors in terms of time varying magnitude and frequency characteristics.

To set up a problem, the user selects or defines an aircraft, describes the trajectory, selects one of the stored weapons, and selects contributing error sources. Contributing error sources which can be selected include sensor errors (e.g., air data computer, AHRS, angle of attack, doppler, inertial system, radar, target tracker), pilot errors (e.g., pipper position, wind, sideslip, bank, steering), computer errors, and post release errors (e.g., release delay uncertainty, ballistic dispersion).

The output is a listing of the contribution of each error source to along-track impact errors as well as the statistical combination of all errors into the total probable miss distance.

5. Survivability

A routine for analyzing aircraft survivability against antiaircraft artillery (AAA) is incorporated in the AEP. This program developed by the U.S. Air Force Armament Test Laboratory (referred to as AFATL Program P001) computes the single shot probability of kill of a target aircraft. Consideration is given to various intrinsic errors in predicting an aircraft/projectile intercept point. Computation of the target aircraft attrition is performed over an entire flight path and the probability of kill results for each increment of the flight path (single shot) are accumulated. The results can be presented in a graphical or tabular manner as a function of several useful parameters at the option of the user.

The major portion of the program is concerned with the analysis of all sources of random error which influence the effectiveness of the antiaircraft artillery. These errors include prediction of an aim point based on the present behavior of the aircraft, firing process errors, and uncertainties and perturbations which arise externally to the weapon system. All of these sources of random error, uncertainty, or perturbation, which in some way contribute to enlarging the final distribution of projectile trajectories, are assessed by the program in order to locate the vulnerable area of the aircraft within this total distribution of trajectories and compute a probability of kill.

Each ground weapon complex is described by its location, number of guns, number of barrels per gun,

projectile parameters, and characteristics of the fire control system. Several sets of gun and projectile parameters may be stored for use in subsequent analyses. The flight path is entered as a series of waypoints. The flight profile generator for the AEP mission models is used to define the aircraft time history. The target aircraft is described by a table of vulnerable areas which are functions of impact angle and closing velocity. Several of these tables may be stored in the interactive system for use in the survivability simulation.

6. Communications

A communications analysis model is available for assessing the likelihood of communicating data over telemetry, command-control, or wide-band video data links. The routine, originally developed for assessing communication links with remotely piloted vehicles (RPV), is currently being utilized for analysis of the vulnerability of tactical data links to enemy jamming.

Tactical elements considered in the model include the control station/aircraft, launch vehicle, weapon or the RPV, multiple jammers, and multiple enemy signal intelligence (SIGINT) stations. For each of those elements, the user can specify typical parameters of the transmitters, receivers, modems, and antennas (e.g., power, frequency, bandwidth, modulation type, noise figure, losses, fade margin, antenna type, main lobe gain, beam width, antenna dimensions, front-to-back ratio). Characteristic data are stored for numerous antenna types and modulation techniques.

Transmission is analyzed over two paths as the vehicles move along predesigned flight profiles--control station/aircraft to weapon and weapon to control station/aircraft. For each path the following sequence of calculation is made: (1) Path lengths, depression angles, off-angles, line-of-sight existence; (2) Path losses; (3) System gains and losses; (4) Carrier-to-noise and carrier-to-jam ratios for friendly and enemy paths.

The model assumes that jamming can occur whenever line-of-sight exists to a SIGINT station and when the SIGINT station receives a signal at a signal-to-noise ratio greater than 3db. Jamming is directed only at the source of signals received by the SIGINT stations.

The model output consists of probabilities of communicating information over each data link versus time in the flight profile.

7. Air-To-Air Mission Analysis

The Air-to-Air AEP mission analysis program is a Monte Carlo simulation of two opposing aircraft flights (up to four aircraft in a flight) through an entire mission. As the flight progresses, it is influenced by hardware failures, refueling, communications to airborne or ground controllers, enemy aircraft detection capability, identification requirements and weapon capabilities. Modeling of these functions varies considerably in level of detail based upon impact on mission success and initial model development priorities. Detailed visual, radar and infrared detection models are available for the target detection function.

When one side (Red or Blue) detects the other, that flight pursues an appropriate tactic and fires when the weapon constraints are satisfied. The encounter is considered only until both sides have detected the other. At that time, the relative positions and headings are stored for output so that users can determine which side has the relative advantage. Kills occur only if weapons are fired before detection by both sides has occurred. At the termination of the engagement, both sides return to the nominal flight profile for the return flight.

Most of the features of the air-to-ground AEP mission analysis program have been retained. A mission is described by the vehicle hardware makeup, flight profile, and mission functions. However, these must be described for both Blue and Red aircraft. All Blue aircraft (and similarly all Red aircraft) must be identically equipped (Blue need not be the same as Red).

The output is composed of statistics describing random variables and the occurrence of discrete events. The outputs, available for both sides, include target detection probabilities, targets detected, targets identified, engagement data, aircraft losses, equipment failures, function/subfunction utilization, and aircraft aborts.

8. Dogfight Analysis

Separate air-to-air dogfight programs have been incorporated in the AEP for analysis of the dogfight encounter. FASTAC, a one-on-one model adapted by Battelle from the Rand TACTICS II model, simulates an engagement between two aircraft. Another model, PACAM, developed by Kearney Associates, allows for simulation of one-on-one, two-on-one, or two-on-two engagements. Both programs produce deterministic trajectories of the dogfight encounter utilizing specific rules for maneuvering. The programs are useful for assessing relative aerodynamic and thrust advantages and for analyzing air-to-air weapons and fire control systems.

To set up a problem, the user selects from the available aircraft, defines the initial conditions, and in the case of PACAM, defines tactical rules for the aircraft. The FASTAC rules of encounter are fixed and are based mainly on an attempt to maximize aircraft energy (speed or altitude) and achieve a closing position on the rear of the other aircraft. In the case of PACAM, the user can select the type of tactics to be used when two-on-one or two-on-two engagements are simulated.

A comprehensive on-line plot capability has been developed to support use of the dogfight analysis programs. Users can plot numerous position, velocity and acceleration components in 2 or 3 dimensions. These plots can be generated in either a fixed reference or any of the moving aircraft coordinate systems. Thus, users can execute one of the dogfight models and then view the resultant trajectories from any angular position relative to the engagement coordinate system.

A separate program exists for analysis of the trajectories produced by the dogfight programs. The user can define firing criteria in terms of the minimum, maximum, and time duration for parameters like range,

angle-off, range rate, etc., which must be satisfied for successful firing to occur. Then, the analysis program will examine the trajectories to define intervals in which the criteria are satisfied.

9. Interactive Graphics

The AEP programs have been incorporated in interactive graphics software packages to provide the user with an easier means of communicating with the computer. Data are entered with simple formats using easily understood acronyms for commands. When a data set has been prepared for execution of one of the AEP models, the processor examines the data for consistency, thus eliminating most of the typical keyboard entry mistakes.

Extensive data storage is available as part of the interactive processor. Thus, data that are entered for execution of one of the models can be stored for later modification and/or re-execution. Where input data are extensive, it is logically subdivided and stored as subsets. Thus, for example, users can separately store hardware reliability data, function performance data, aerodynamic data, and flight profiles for use in the air-to-air or air-to-ground mission analysis programs.

A very important "help" file and a complete on-line user's manual are available to aid the user in communicating with the processor and associated programs. On-line help is requested by entering a question mark in any portion of the interactive processor. Available commands are listed and can then be described in more detail if desired. Formats for entering commands are provided along with typical examples.

The incorporation of interactive graphics was an important milestone in the application of the AEP. Mathematical modeling of air weapon systems/subsystems is a very common activity. However, development of a library of detailed avionics assessment models directly available (via telephone line) to design engineers, operations research analysts, managers, and SPO personnel scattered throughout the DOD and industry is a unique effort. In addition, the use of interactive graphics allows rapid response answers to analytic questions that arise. Once an aircraft has been initially examined in a given scenario (and the associated input data conveniently stored), "what if" questions can be answered in a matter of hours rather than the typical days, weeks, or months. Thus, the models can become a useful tool of the planner/manager, providing timely input to the decision-making process.

10. Conclusion

The AEP provides the Air Force and the DoD with a collection of well-documented, well-understood computerized models for performing detailed trade-off analyses of air weapon system configurations. The availability of these programs to contractors as Government Furnished Equipment in support of specific DoD efforts, significantly reduces expenditures for contractor and hence, for the DoD. In conclusion, these programs provide the Air Force Avionics Laboratory with an efficient tool for conducting in-house analyses of current and postulated avionic systems in a wide spectrum of operational environments.

SIMULATION FOR WHOLE LIFE DEVELOPMENT

R.J. MORROW and R. RICHARDS

BRITISH AEROSPACE, DYNAMICS GROUP

GPO BOX No 77, BRISTOL BS99 7AR. U.K.

SUMMARY

This paper is devoted to a description of a special purpose, real-time simulator suitable for whole life development of complex avionics control systems. Software flexibility, a current equipment selling point, demands a re-appraisal of previous equipment development procedures. No longer may a control processor be assumed to have been fully developed when installed. Rather an on-going whole life development programme is needed. It is in this area that new simulation techniques can play a significant part. Future problems with high speed information handling will occur during the development of new digital controllers when used for command and control, ESM and EW systems. The need is to simulate those real world factors that load the information to the digital processing system under development. A solution is proposed. The way forward is to simulate the multi-element real world as a set of autonomous information generating sources using large parallel processing arrays. The demanded high information rates are achieved by multiplexing the output of the individual elements in the array. When this is coupled with a simplicity of simulator control and a means of software simulation of the individual scenario elements the solution has wide application. Further by simulating totally in the digital domain, direct interface with the physical processing equipment may be realised. In this manner whole life development may be achieved with the simulator in use during the feasibility phase to test alternative software/hardware strategies. Then during the development phase to complement practical trials, and finally in the operational phase to revise and improve software according to tactical dictates.

1. INTRODUCTION

The recent advances in the field of micro electronics offers a promise of better equipment solutions to a wide range of military requirements. The military avionics and weapon fields are typical in this respect. If viewed as a whole an aircraft has numerous real-time electronic processing requirements and it is self evident that military standard, microprocessor based structures will increasingly take the burden of growth in system capability. This potential is already having an impact on the design of avionics for the newest fighter aircraft (Countermeasures, 1976) and in the research programmes dealing with integrated avionics with high reliability (Dryst J.J., Hopkins A.L., 1978), control and display (Kopchick A.N., Premselaar S.J. 1976) and electronic warfare (Doyle W.C. 1979). The future use of computers will eventually radically change ideas about the design, development, manufacture and maintenance of real-time control systems. The current levels of research and development into the hardware and software design of real-time control systems require a complementary interest in test and development equipment. The revolution of the microcomputer has been complemented by the supporting microcomputer development aids (Lin W.C. 1977). It is therefore judged important to develop increasingly sophisticated system level test and development equipment.

Further, to realise the important benefits of this new technology: that of redesign by software update, the system level testing must be thought of as a whole life function. With these concepts in mind the design of a general system level, test equipment has been researched and equipment developed to demonstrate the idea.

2. WHOLE LIFE DEVELOPMENT

To place in context the need for new approaches to system level test and development facilities, the theme of Whole Life Development as the basis for the procurement of future control systems using centralised or distributed control computers has been chosen. The hardware economics of microprocessor electronics belie the true cost incurred through the design, development and test support needed to produce the software product. The traditional approach has used monolithic centralised control structures, general purpose military standard computers and standard real-time languages in an attempt to reduce the software development and maintenance overheads. Alternative design strategies are currently emerging where the problem is mapped to an optimum joint design of the machine structure and the supporting software architecture. The driving force for alternative designs is for reduced complexity of the software task and in turn a reduction in the problem in validation and in-service maintenance costs (Gordon D., Spencer R.D., 1977). Unfortunately, the underlying objective of most military equipment requirements is the transfer of complexity to the machine. Thus it is anticipated that the problem of system validation is going to increase as we strive to meet these requirements. For this reason it was thought worth while investigating the problem of system test in detail taking into account the recent advances in computer technology.

The extensive use of general purpose computers is an accepted appraoch to the development of real-time control systems. In the feasibility and project definition stages general purpose computers are used to program and run system models of competing solutions leading to the definition of the control algorithms. Following this, during the development phase, general purpose computers are again used to produce correct software and, during the course of system test, to simulate operational inputs to the control processor. Finally, during the in-service life of the equipment general purpose computers may be used for software maintenance and program update and test. In the general course of events this ad hoc use of computer facilities is not necessarily the most economic approach. For this reason it is suggested that the use of a specially designed, system level, development facility can offer significant advantages.

In terms of a real-time control processor development programme this facility would need to have the following features:

* Software simulation of the total problem.
* Real-time test data generation mode.
* Direct hardware interface to prototype control processor.
* Simple to use operator interface for testing.

These features allow the facility to be used at all stages, including in-service software update, this feature representing a dominant programme requirement for certain military systems (Butland R.N., Maher R.A.). The economics of this approach have to be derived for each particular project. These are presently based on the cost of using general purpose computer facilities during development and later when in-service, as opposed to the cost of procuring a single special-to-type facility on which all the software can be developed. This latter approach benefits from not being subject to inflation and immune to cost escalation resulting from procuring additional computer capacity to meet unforeseen problems.

3. SIMULATION AND SIMULATOR STRUCTURES

In practice real-time control processors are used for many applications: missile control systems, ESM systems, ECM control systems, display systems etc. For this reason a general control problem has been selected to illustrate the chosen simulator solution. It is left to the reader to infer the relevance of the solution to particular control system applications.

The generalised control system problem is shown in Figure 1. The processor has a real-time control strategy based on the use of sensed analogue information which is provided by one or more sensors. This information is digitised and fed to a central processor structure. The control processor responds to the sensed data to alter the platform flight profile and elements of the real world referenced to the sensors. Certain major parameters are displayed and updated for use by a human operator.

The simulation requirements are two fold : a system model and a data generation test model. The former is characterised by the relaxation of the requirement for real time plus the fact that the control processor's operation may be incorporated as a system model. In the case of the test model the simulator must adequately represent all those elements except the control processor such that the input and output data streams are representative of operational condition. Further, in order to have the necessary degree of flexibility, all major parameters must be accessable to the simulator user with a simplicity of human interface to allow change and recording of test conditions.

The design of a simulator that meets these requirements has to be approached with some caution. Although flexibility is necessary - thus the choice of a computer based structure - complex software and high development costs are not. Additionally, as a test instrument its standard of reliability and error diagnostics must be high so as not to jeopardise any developmemt programme. In general the standard for choosing the simulator design should be as high, if not higher, than that for the control processor structure. One exception is the build standard where there is the freedom to use commercial electronic products with their cost advantages.

The simplest simulator configuration is a standard general purpose computer and high level language. In general the system model may be realised without difficulty, but a direct application to testing is limited by the computer's maximum instruction rate and I/O facilities. In terms of commercially available computers, a need for realism of simulation with correct I/O rates inevitably leads to main frame operating performance being required. This occurs in many cases because the distributed characteristics of the real world do not map directly to sequentially operating computers. Modular distributed computer structures offer significant advantages in this respect. Returning to the problem illustration, Figure 1, parallel information may be said to exist at the environment to sensor(s) and sensor(s) to control processor interfaces. These areas are candidates for distributed computer simulation. In general if the global problem can be specified as a set of N elemental data generators with defined input and output, then a set of N independent processors may be used, Figure 2. This approach leads to a restatement of the problem illustration, as shown in Figure 3. With this form of distributed intelligence system, tasks assigned to elements in the multiple computer configuration remain fixed. When programmed, elements in the structure act as digital transfer functions passing transformed input data to a subsequent stage of simulation, i.e. platform motion - environment-sensor(s) - control processor. Platform motion is thus defined as the forcing function for the first array. This data is required by all units and thus leads to the definition of a master-slaves organisation with interconnection via a bidirectional highway. Such a configuration permits the following functions to be performed.

* Simulation program loading.
* Periodic flight profile update.
* Monitor of states of individual simulation units.

The next stage of interconnection is from the first array to the second. This simulates the sensors interrogating the environment. This is incorporated using a unidirectional highway under the control of the computers representing sensors. The same conditions apply to the sensor(s) to control processor link.

The potential benefit of this approach to problem reduction, where parallelism is stressed, is gained through the low cost, size and power consumption of microprocessor based microcomputers. It has been

recognised that it may be more economical to use many processors than to upgrade to a faster basic machine and formal approaches to problem reduction are under study (Dowsing and Dagless, 1979). With this approach to simulator design using a parallel distributed computer structure, the problems of real time simulation are overcome but not at the expense of software simulation flexibility. Further if a generalised modular microcomputer design is used the hardware economics of the structure can compare favourably with the cost of solutions based on mid range computers.

To investigate the operational performance of this approach to a general purpose simulator and to establish the level of complexity of the programming task a microcomputer array simulator has been constructed. This is designed to simulated control problems of the type illustrated in Figure 1.

The hardware build programme has centred on the design and build of an expandable microcomputer array and its input and output interfaces. For the first stage of simulation (the input to the array), and the third stage of the simuation, (processing the multiplexed data output) commercially available mini computers were selected. The overall feed-back loop is then closed via a link between these mini computers to arrive at the equivalent of Figure 1. This configuration allows investigation of all major hardware and software features of the approach, namely:

* Array program loading
* Simulation house keeping
* Simulation software design
* Parallel asynchronous operation
* Real time data transfer and time ordering
* Modular hardware design

4. A MICROCOMPUTER ARRAY SIMULATOR

One of the main criteria in the design of the simulator was that system elements should be independent i.e. modification of any one element should not necessarily result in the modification of any other system element. The baseline system requirements were :

* real time simulation
* autonomous simulating elements
* modular construction, hardware and software
* overall system operating speed not to be governed by slowest element
* communication between elements
* one element should have executive control

An investigation was undertaken into the size of array that would be required to simulate the typical environment. It became, meanwhile, apparent that the element acting as executive would be required to be significantly more powerful than other elements in the array. The conclusions were that the system should include up to 256 simulating elements (microcomputer) linked to a single dedicated executive (mini computer) and a system output capability of up to one million words per second, Figure 4.

Executive Control

The function of the Executive is to provide an interface for the human operator and also to provide system housekeeping. A standard minicomputer (PDP11) plus peripherals was chosen for this purpose, Fig. 5. The choice of such a minicomputer system permits its use for microcomputer program development. In this mode the minicomputer is supported by the RT-11 operating system and a cross assembler written specifically for the purpose. The RK05 high speed disc system is used for program development (replacing an original much slower paper-tape system) and storage of software models. A library of models is stored on disc permitting loading into the respective microcomputer memory as demanded by the operator, via the input bus. Display information is output to a colour V D U using a V T 30 interface card. Keyboard and printer are standard peripherals. The input bus is designed to permit system flexibility. Data transfer is asynchronous, the handshake is software controlled, no special purpose hardware controller is required at the Executive to undertake the bidirectional data transfer.

Simulating Elements

The Simulating Element has been designed as a general purpose microcomputer having the minimum of hardware interface constraints. Two I/O ports are provided, each permitting parallel word data transfer to maximise operating speed.
The microcomputers are designed around the Intersil 6100 microprocessor. (Thomas A.T. 1976). This is a 12 bit processor in CMOS which recognizes the instruction set of the PDP8/E minicomputer. A block diagram of the microcomputer is shown in Fig.6. Of the 4K memory directly addressable by the 6100, 256 words are in PROM (containing the loader) and the remainder in RAM. In fact 4K of RAM is fitted but the top 256 words are not used. Each microcomputer is built on an extended double Eurocard and the design and manufacture has been completed by BAe. All the Simulating Elements (microcomputers) are identical including the PROM software (but excluding RAM software). The gain identity from their physical location within the system i.e. each board location is uniquely addressable. The design permits up to 256 autonomous Simulating Elements. The Input Bus data I/O is controlled by a Peripheral Interface Element (PIE), 6 Control lines are used for device selection and data flow direction. A second I/O port is provided, and, although configured as a completely general purpose port, its use in the present system is limited to data destined for the system output bus.

Input Bus

The Input Bus Interface Board provides all the buffering and bus separation circuitry required for interfacing the microcomputers with the DR11C output from the PDP11. It is designed to interface up to 16 cards (one card frame) and buffer those signals required by the following card frame. It also provides the latching and decoding required for board addressing. A schematic diagram of the Interface Board is shown in Fig. 7. It is housed on a single p.c.b. of the same size as a microcomputer board. The bidirectional input bus comprises 12 data lines and 6 control lines. Bus data direction is controlled by the PDP-11, and data transfer is on a word by word basis under control of three handshake (H/S) lines. Data may be transferred in one of four modes:-

From Executive-Unique	:	data word is loaded to uniquely addressed microcomputer.
From Executive-Global	:	data word is loaded simultaneously to all microcomputers.
To Executive Unique	:	Executive requests/accepts data from specific microcomputer.
To Executive Global	:	a number of microcomputers have data for Executive which instigates a non-ambiguous sequential selection process to accept this data.

A transfer of data between the Executive and microcomputer can consist of any number of words as determined by the software. The interface is designed for 12 bit data words, but the use of a general purpose (DR11-C) I/O to the Executive (PDP-11) enables the system to be relatively easily modified to cope with 16 bit data.

Real Time Data Output

The system is designed to output real time data, with a timing resolution of 1 uS. Each microcomputer is accessed for data on a sequential basis. A data block is output at each interrogation, this block represents data that is to occur during a subsequent defined time frame. Currently this time frame is 1mS. By outputting data in blocks the ratio of the peak to mean data rate on the output bus is low. The output bus is 16 bits wide to cope with future system updating. Every microcomputer is interrupted each 1mS Fig. 8, it must then generate the data descriptions for that time frame, time tagging them to 1 uS resolution. This data is then read into one half of a double buffer store, Fig.9. Whilst this data generation is performed the other half of the double buffer store (containing the data from the previous 1 mS) is available for writing to the output bus when accessed. Since all microcomputers may generate data autonomously and are accessed sequentially, the data appearing on the bus is not necessarily in correct time sequence. To correct this, the data is read into the Sorting Buffer where it is time ordered (using the 1uS time tags) and output in a perfectly ordered time sequence. The Sorting Buffer is also designed to handle time overlapping data. The system timing ensures that all microcomputer output data timing is synchronized. Since there is a limiting value to the data rate that any microcomputer can achieve, this synchronization is used to interleave data streams from more than one microcomputer to produce a higher, composite, data rate from any one element. The system permits more than one Sorting Buffer to be linked to the Output Bus, providing simultaneous real time outputs to one or more Devices Under Test (DUT). Special purpose interfaces are required for different DUTS.
The DUT is stimulated by the input data and its output, if required, may be connected back to the Input Bus, Fig. 4. and subsequently to the microcomputers to produce a totally interactive system.

Packaging

A modular packaging system is used, based on the Eurocard system. Standard card frames house extended double Eurocard size pcbs. Each card frame contains card mounted power supplies. This form of packaging allows for ease of maintenance (by replacement on site and repair back at base) and flexibility in expansion and development.

5. OPERATING PRINCIPLES

The choice of high or low level language depends on whether any specific program is to be run on the minicomputer or microcomputer(s). With less than 4K of memory available in each microcomputer, code compactness is important. This factor, plus the requirement that programs are to be executed in real time, dictates the choice of a low level language for the microcomputer software. Whilst the use of a high level language might ease the problem of finding suitable programmers to write the software, this advantage is more than offset by the (unrealistic) requirement to have an intimate knowledge of the appropriate compiler(s) to predict storage and timing.
These requirements do not normally exist when writing software for the minicomputer. The program currently being executed is held in core, with access if required to data held on disc. i.e. storage efficiency is not critical.

Efficient Program Execution

The generation of real time data from the microcomputer array to represent the physical environment as observed by the sensors can result in programs that contain complicated mathematical routines. The execution time of such programs can be comparatively long resulting in low maximum simulated data rates. This is a function of the microprocessor chosen, the next generation of 16 bit machines offer only a partial solution. An alternative technique that has been employed is to use a table of values to represent the function. This approach allows the mathematical routine to be efficiently evaluated using a high level language on the minicomputer, and a Table constructed. The table(s) then forms part of the microcomputer program. With this approach the maximum data rate may be increased as a trade off against simulation accuracy and microcomputer memory size. Certain of the important concepts may be illustrated using an airborne ESM problem. The solution involves representing each of the distributed emitters as individual contributors to the multiplexed data input to the ESM Control processor. This is achieved using individual microcomputers to represent individual emitters. The time multiplexed

data at the output of the microcomputer array is thus equivalent to that input to the control processor, and can be used for development or test purposes. Individual emitters are defined using their main parameters, e.g. amplitude, frequency, pulse width, pulse repetition interval, and are implemented as word generators, with each word containing the current value of these parameters. The variation in time of the parameter value is a characteristic of both the design of the emitter and its positional relationship to the airborne platform. The design of the emitter is incorporated into the software emitter model. For example a radar's scan pattern can be defined mathematically and hence the pulse amplitude envelope for a pulse radar, as seen at any point in space, may be calculated using a high level language routine on the minicomputer. This may be stored as a look-up table for loading with the emitter simulation program. As all emitters are related to the airborne platform's position it is convenient to give periodic positional updates from the minicomputer to all microcomputers. In this manner the platform's position relative to the radar's pointing direction may be calculated using the microcomputer program, and the appropriate amplitude value selected from the pre-computed table. This amplitude value may be modified according to the range to give a correct interpretation of the change in received signal strength. Similarly values of frequency and pulse width may be selected from look-up tables. The value for the pulse repetition interval is directly related to the time of occurrance of the data as received by the control processor under test. This is achieved by time stamping the data at source (microprocessor) and then, at the output of the multiplexed highway, ordering the data in the correct time sequence.

With this simulation all major parameters are software flexible and the whole acts as both a system level model and a real time test generator. The control processor strategy may be introduced through the use of a second mini-computer coupled to the output of the microcomputer array. Alternatively the control processor itself may be included in the loop. The use of a minicomputer as the executive control interface allows provision of standard peripherals to simplify the human interface. Typically, visual display hard copy and magnetic disc storage allow a high level operator interface to be constructed providing in the case of this problem, options for :

* emitter selection and deployment
* flight profile compilation
* real time display of major interactions
* hard copy listings of both input set up data and run data
* repeat of test conditions

6. CONCLUSION

A versatile digital simulator has been constructed. This simulator takes full advantage of the low cost of microprocessor electronics with a design based on the use of a large microcomputer array. This approach simplifies the problem of implementing a software flexible, real time test data simulator and offers the basis for a unified approach to system modelling. The results indicate that this approach to computer simulation for system design, test and software maintenance may offer an economic alternative for certain projects where real-time process control is to be implemented using software as the major element of in service flexibility. Software development and testing requires an investment in system level tooks to take full advantage of the benefits offered by current and future processor electronics. This simulator is an example of the possible use of the same electronics but applied to the construction of a test equipment.

7. ACKNOWLEDGEMENTS

The authors wish to thank their colleagues at British Aerospace, Dynamics Group, Bristol who have contributed to the development of the simulator described in this paper. In particular to M.J.Letharen for his important contribution to the software engineering of the system. The authors would also like to thank the Directors of British Aerospace, Dynamics Group, Stevenage - Bristol Division for permission to publish this paper.

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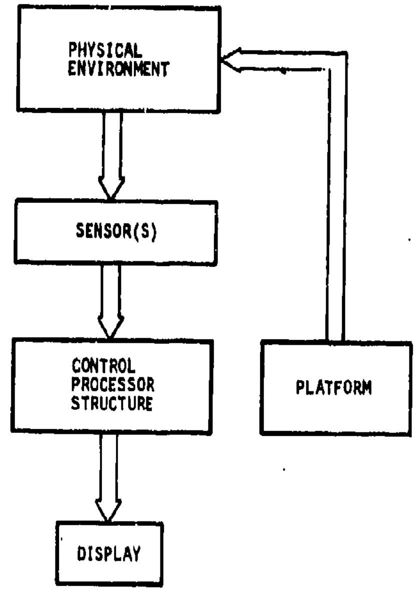

Fig.1 Problem illustration

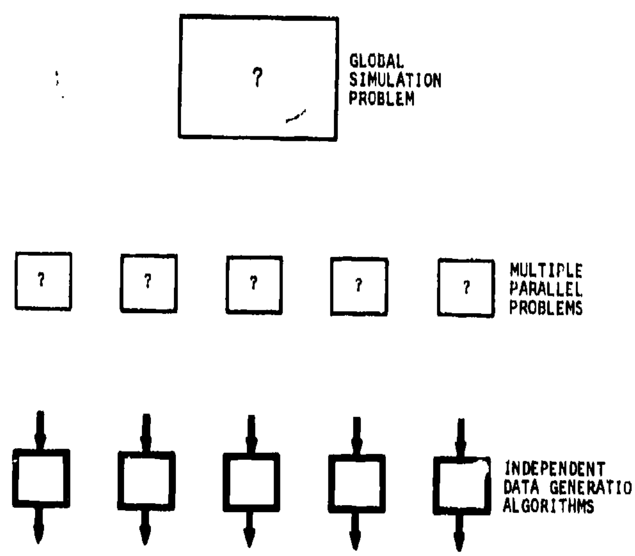

Fig.2 Problem reduction

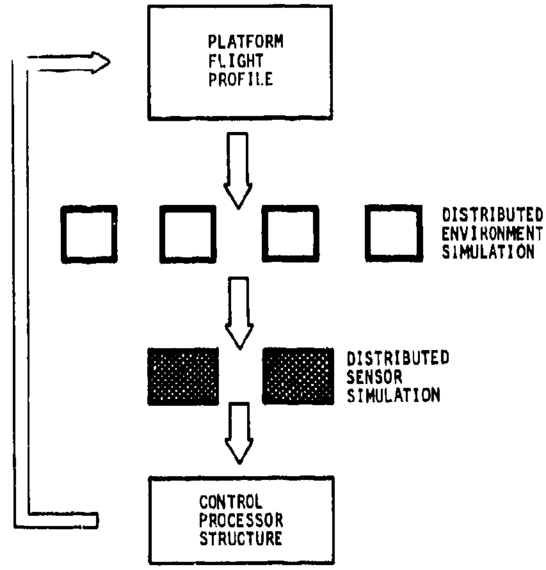

Fig.3 Reconfigured problem

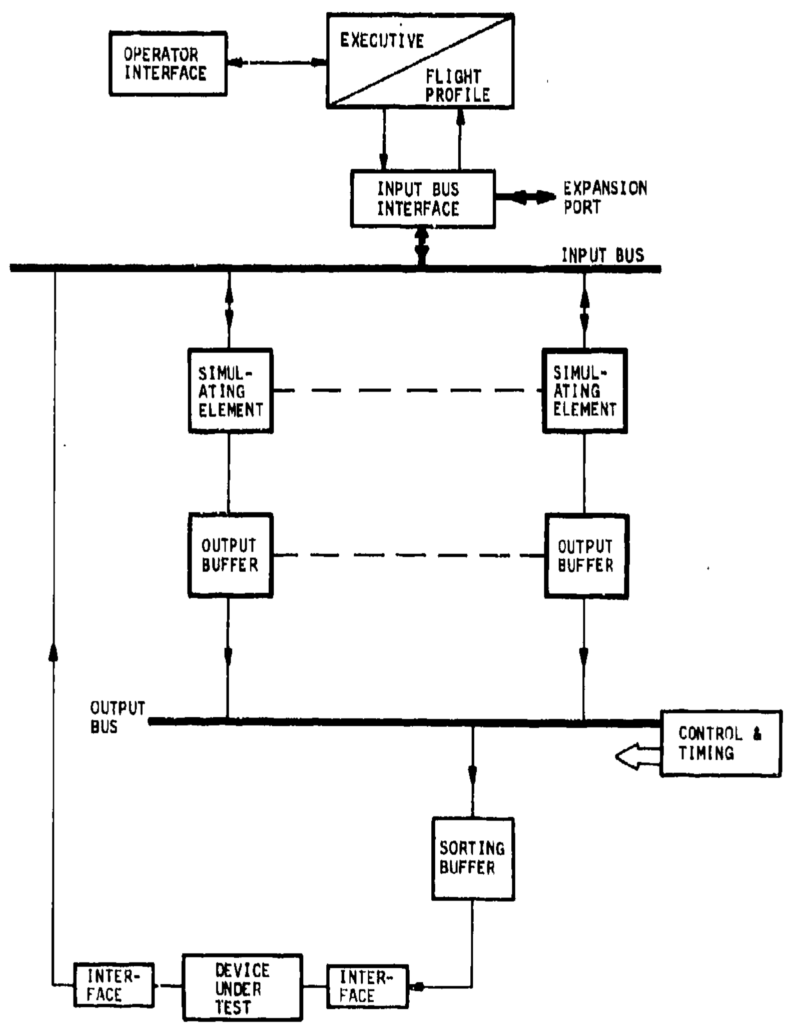

Fig.4 System block diagram

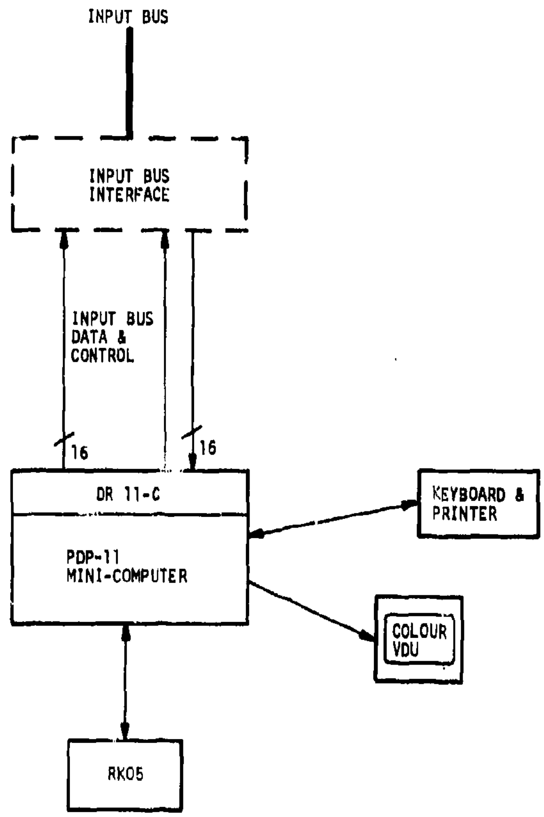

Fig.5 Executive computer system configuration

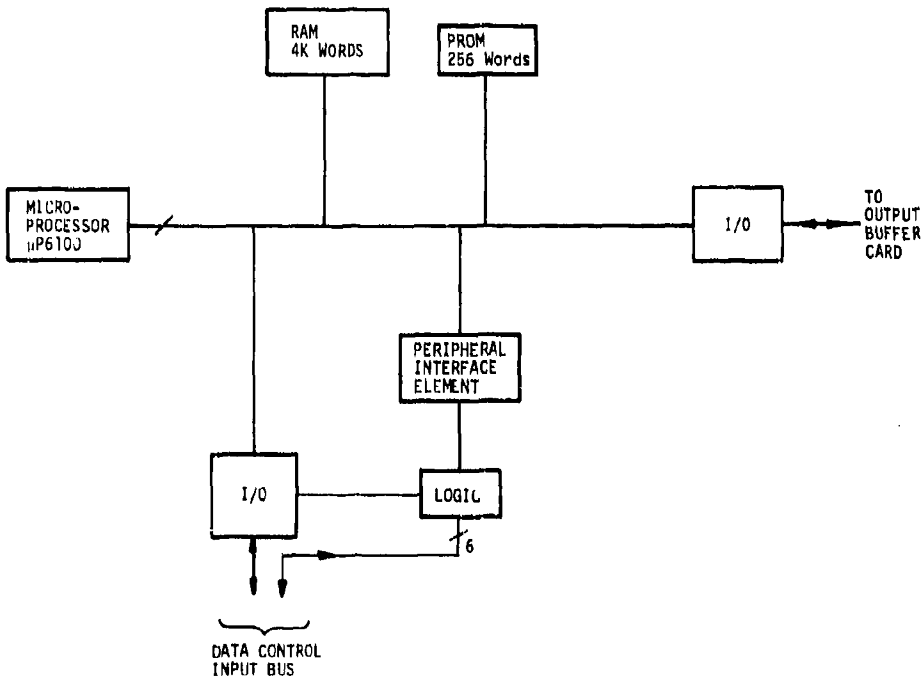

Fig.6 Microcomputer block diagram

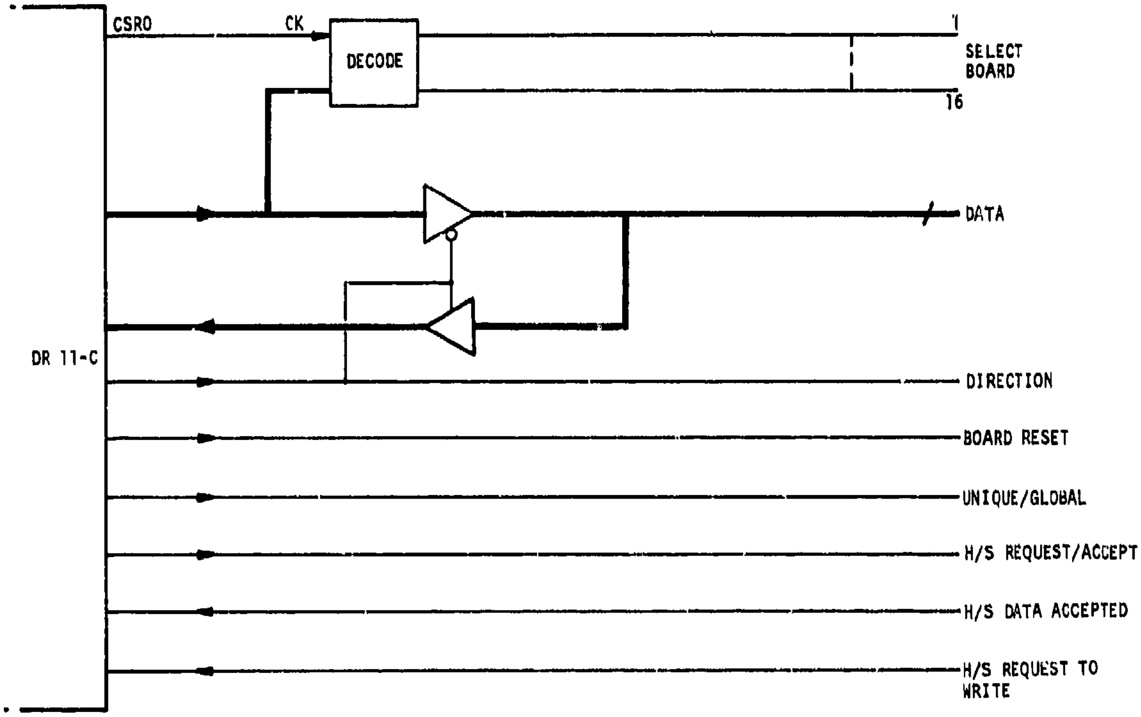

Fig.7 Input bus interface

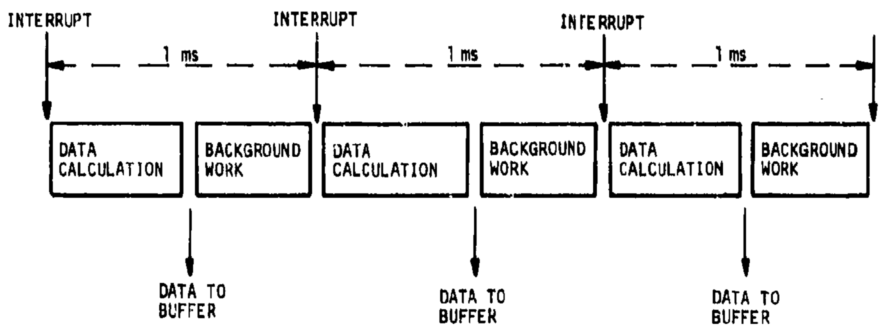

Fig.8 Data generation timing

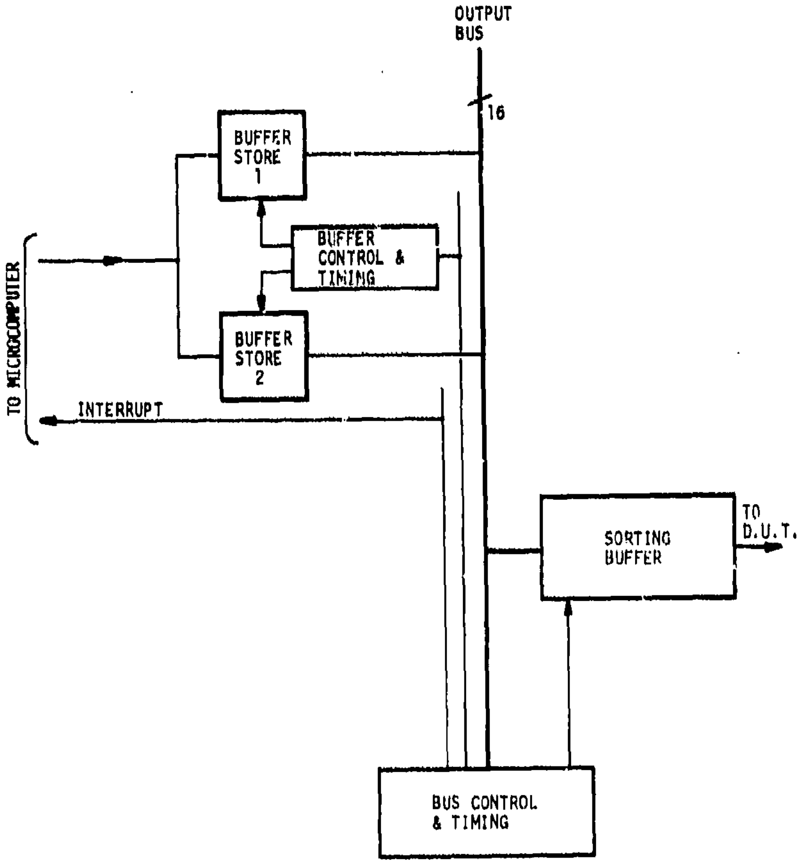

Fig.9 Output buffer

A SIMULATION SUPPORT SYSTEM
THE DEVELOPMENT TOOL FOR AVIONIC
SYSTEMS AND SUBSYSTEMS

John C. Ostgaard
Air Force Avionics Laboratory
Wright-Patterson Air Force Base, Ohio

SUMMARY

As Avionic systems have grown both in cost and complexity, more emphasis has been placed on simulation support systems capable of validating and verifying such systems prior to actual implementation. This paper encompasses the simulation support facility required for the development and validation of the Digital Avionics Information System (DAIS) program currently being conducted at the Air Force Avionics Laboratory, Wright-Patterson Air Force Base.

The simulation support system is composed of three main elements - simulation support hardware, simulation support software, and a host simulation computing complex. The Support Hardware System includes those interfaces required for the generation of a data signal environment between the simulation and the DAIS avionic suite. The Simulation Support Software is comprised of software necessary for the simulation of flight data, as well as those programs which monitor, record and control the data from both the simulation and the actual flight hardware. The Host Simulation Computing Complex generates the simulation mechanisms necessary for the real-time emulation of airborne systems. The coordination of these three elements provide a flexible support system capable of control, simulation, monitor, record and analysis functions.

1. INTRODUCTION

In the past, development or augmentation of avionics systems have required extensive investment in special purpose hardware and software necessary for the simulation support of these avionics systems. The simulation systems have been point-designed to the actual avionics system requirements and have not included the generic capability required for a flexible and easily reconfigurable Simulation Support System.

The development of the Digital Avionics Information System (DAIS), which is a program currently being conducted at the Air Force Avionics Laboratory, Wright-Patterson Air Force Base, required a flexible simulation support facility capable of simulation, control, monitor and record functions. These capabilities have been used to verify and validate the system architecture, in both real-time and non real-time modes of operation. The basic design of the support facility was based upon the requirements of the DAIS program; the system, however, is not limited to that specific architecture and has many features included within it to give it widespread usage. To allow for a better understanding of the Simulation Support System, a brief explanation of the DAIS architecture is included.

The Digital Avionic Information System is a system architecture which can be configured for various avionic applications and missions, using core elements or building blocks. The purpose of the DAIS concept is to reduce the proliferation and non-standardization of aircraft avionics, and permit the Air Force to assume the initiative in the specification of standard avionic systems and interfaces for future Air Force System acquisitions.

Historically, avionic systems have been established along semi-autonomous functional areas such as navigation, weapon delivery, flight control, communications, etc. Each of these functional areas would have a digital system with its own processing, information transfer, control inputs, and display set. There has been an interface between each functional area only as necessary for interaction purposes, using non-standard interfaces. The DAIS concept proposes that the processing, information transfer, control and display functions be common and service all the previously described functional areas on an integrated basis.

The DAIS architecture as shown in Figure 1 consists of processors, which communicate with each other and with the sensors, weapons, controls, and displays through a dual redundant (MIL-STD-1553) multiplex data bus system under control of mission software. The mission software is comprised of application software, which performs the processing required for a specific aircraft mission application, and the executive software, which performs the system control and provides services to the application software.

2. REQUIREMENTS

The design of an integrated Simulation Support System must allow for six fundamental areas of flexibility. These areas are depicted in Figure 2 and briefly described herein:

(1) Avionic System Support.

(2) Prototype System Software Support.

(3) Prototype System Hardware Support.

(4) Engineering Studies.

(5) Maintenance Augmentation.

(6) Training Assistance.

A simulation support facility must have the flexibility of supporting an avionic system design throughout all stages of development. These stages include initial design analysis, prototype development (both hardware and software), complete system definition/implementation, and verification and validation. Within this entire development, integration procedures, system testing procedures and maintenance procedures should be defined and established. A system designed using such a facility should be capable of providing the necessary documentation and data to allow for complete system integration within an aircraft with minimal risk. Furthermore, problems encountered during flight testing should be reproducible within the simulation support system.

3. GENERAL DESCRIPTION

The simulation support system provides a real-time simulation of a military aircraft performing an operational mission. The simulation generates the interface signals between the simulated aircraft sensor suite and the DAIS system so that the avionic equipment is subjected to a data signal environment which is nearly identical to actual flight.

The support system required for DAIS is comprised of a Software Test Stand (STS) and an Integrated Test Bed (ITB). The Software Test Stand is used primarily to verify the mission software resident in the DAIS flight processors. The Integrated Test Bed provides the capability to evaluate the DAIS core elements which include the mission software, the DAIS processors, the data transfer system, and the cockpit control and displays. The Software Test Stand is currently a subset of the Integrated Test Bed, so for purposes of discussion the Software Test Stand will no longer be included when discussing the support system.

The support system and its relationship to the DAIS core elements is shown in Figure 3. The support system is comprised of a network of four computer systems, simulation interface hardware, and supporting software which interface to the DAIS avionics via the MIL-STD-1553 Multiplex Data Bus. The Simulation Support System is partitioned into basic functional elements which are distributed among four individual computer systems. These elements include the DEC system - 10 Models, Simulated Subsystem Data Formatter System (SSDF), Performance Monitor and Control System (PMC), and the Evans and Sutherland (E&S) Graphics System. These systems are interfaced via a direct memory access channel (DMA-10) which provides the capability of shared memory.

4. SIMULATION SUPPORT HARDWARE

The support hardware provides the interfaces between the simulation and the DAIS core elements. These interfaces include: simulated multiplex bus messages which drive the mission software, performance monitoring of the multiplex bus traffic and internal operation of the DAIS processor, as well as control of the mission software resident in the DAIS processors.

The Simulation Support System contains the following support equipment:

(1) Universal Remote Terminal (URT).

(2) Bus Monitor Unit (BMU).

(3) Super Control and Display Unit (SCADU).

(4) Additional interfaces as follows:

- (a) Four-Port Buffer Memory.
- (b) PDP-11 SCADU.
- (c) RS 232 Processor Load/Control Channels.
- (d) TCC Stick and Keyboard.

4.1. Universal Remote Terminal

The Universal Remote Terminal (URT) is a programmable interface device designed to simulate the responses of any or all Remote Terminals (RTs) and their associated subaddresses on a MIL-STD-1553 multiplex bus (Mux Bus). The URT is comprised of four sections. The first section is the Bus Interface Module (BIM) which provides an interface between the control unit of the URT and the mux bus. The second is the Unibus Interface Module which provides the interface between a PDP-11 Unibus and a user's device. The third section is the Terminal Control Module (TCM) which provides the timing and control logic necessary to implement the URT's control procedures. The fourth section is the Response/Mapping RAM Module (RAM Module) through which the URT's responses can be specified. Commands on the mux bus are received by the BIM and responses are initiated by the TCM. Data words are received by and transmitted from the URT across the mux bus in response to the command received. This data is mapped to and from the PDP-11 memory space as determined by the main RAM mapping address. Special RAMs are also implemented on the RAM Module to store status, activity, message error, and last command information for each RT (Ø-31).

The URT is set up and controlled by the SSDF software resident in the PDP 11/40 by loading the appropriate URT registers and RAMs. In real-time operation, the URT performs the following operations: Transfers DAIS multiplex data to/from the PDP-11 for each message operation, responds to mode commands in accordance to DAIS multiplex protocol, simulates subsystems error and activity, and responds with predefined errors on the multiplex data bus.

4.2. Bus Monitor Unit

The Bus Monitor Unit (BMU) receives, records and breakpoints on selected messages on the DAIS multiplex data bus. The BMU when monitoring the data bus acts as a passive device and stores the received messages in a PDP 11/40. The BMU has the capability to provide selective monitoring as follows:

(1) Record the bus traffic beginning at a specified breakpoint and for a specific number of words.

(2) Record the bus traffic beginning at a specified breakpoint and for a specific length of time.

(3) Record the bus traffic beginning at a specified breakpoint and until a second specified breakpoint is encountered.

(4) Record the bus traffic beginning at a specific breakpoint and until the end of the message.

(5) Record all bus traffic, only control words, or only data words.

(6) Transmit a message.

The BMU also has a manual control function directly controlled from the BMU front panel. This mode of operation stores the last 64 designated words on the bus which means all words, only control words, only data words, or only message gap times.

4.3. Super Control and Display Unit

The Super Control and Display Unit (SCADU) provides the system programmer with monitor and control capabilities of the Operational Flight Program in the AN/AYK-15 flight processor. The monitor and control functions are performed in real-time by the SCADU hardware without the insertion of special purpose software into the operational software. The SCADU is organized into a Processor Interface Module, a Unibus Interface Module, a Data Buffer, and the Control Unit. The Control Unit is further subdivided into the Main and Secondary Control RAMs, the Data Comparator, Programmed Input/Output (PI/O) Control logic, the Discrete Control Decoder, the wrap-around Self-Test logic, and various counters and registers for command, status, time-tagging, etc.

In conjunction with the PMC software, the SCADU is set up to collect, store, and/or breakpoint on the data received from the DAIS processor. Once fully initialized the SCADU performs one or more of the following monitor functions:

(1) Monitor all instructions addresses.

(2) Monitor specific instruction (Op-code).

(3) Monitor all jump instructions which cause a branch.

(4) Monitor all memory stores.

(5) Monitor all memory accesses.

(6) Monitor all interrupt occurrences.

(7) Monitor all DMA occurrences.

The SCADU may also perform one or more of the following control actions:

(1) Breakpoint (halt) upon occurrence of one of the specific functions above.

(2) Log the data in SCADU buffer (trace) with a time tag.

(3) Compare the function with user's specific value (fixed point or floating point numbers) and breakpoint.

(4) Halt processors and BCIUs.

4.4. Additional Equipment

Other equipments used in the Support System though not major hardware developments, do allow for easier communication and data updates within the array of PDP 11/40 mini-computers.

The Four-port buffer memory is a 4K slice of semi-conductor memory which can be shared by up to four PDP 11/40 processors. All segments of the memory can be accessed by each of the PDP 11/40 processors.

The PDP 11 Super Control and Display Unit is a device which allows for the control of up to three PDP 11/40s from a fourth PDP 11/40. The master PDP 11/40 has the capability to interrupt and pass data to each of the slave PDP 11/40s. The slave PDP 11/40s can pass data to the master PDP 11/40 and can also interrupt the master if the master hasn't disabled the interrupt.

The Controls and Backup Instruments System (CBIS) is the interface between the PDP 11/40 and the DAIS cockpit. Information such as stick and throttle data is provided to the PDP 11/40 and thus entered into the simulation.

The TCC stick and keyboard is an interface which allows the operator to fly the simulation from the Test Conductors Console rather than from the cockpit.

The Console Intelligence Unit (CIU), in conjunction with an RS-232 channel, interfaced with the PMC PDP 11/40, DEC-10, and the Hazeltine terminals, provides the means to control, and load/change DAIS processor registers and memory. The CIU is supplied by the DAIS processor vendor to support the debug and test of the mission software under non-real time conditions.

5. SIMULATION SUPPORT SOFTWARE

The Support Software is divided into two basic systems, the Performance Monitor and Control (PMC) system and the Simulated Subsystem Data Formatter (SSDF) System. The PMC software controls those interfaces required for the monitoring and control of the DAIS avionic suite. The SSDF software is responsible for the routing of data from the DAIS core elements to the host simulation system.

5.1 Performance Monitor and Control System

The Performance Monitor and Control (PMC) software has the capability to initialize, control, and monitor the mission software resident in the DAIS processors for testing and evaluation purposes only. The PMC software is resident in a PDP 11/40 computer and supports the system users in the loading, debugging, and evaluation of mission software by allowing selective real-time and non-real-time gathering of data from the DAIS processors (AN/AYK-15s) and the multiplex bus. The PMC is capable of servicing from one to four DAIS processors at one time while simultaneously monitoring the multiplex bus traffic via the BMU and recording selected DAIS system data for post test analysis. The PMC is capable of test set up to define the processors and data collection for a simulation run. Through an interactive interface the operator can create a test control file correlated with the DEC-10 simulation, so that the collection of test data can be mapped with the progression of the simulation. The PMC provides the capability to restart mission software, along with the simulation models, from a system snapshot point. This is accomplished by dumping mission software parameters at a specified PMC breakpoint, and reloading these parameters to restart the system. This snapshot and restart capability is used for repeated testing or demonstrations from a specific point in the mission profile.

The following list defines the non-real-time and real-time functions provided by the PMC:

(1) Manipulate files on the DEC-10 and PDP-11.

(2) Load or dump DAIS processor mission software from or to the DEC-10 or PDP-11.

(3) Set or reset program path breakpoints when the DAIS processors are halted.

(4) Start and stop (halt) the DAIS processors and BCIUs (single step or continuous execution).

(5) Set up and control the SCADU to collect, store, and/or breakpoint on the data received from the DAIS processor, and then halt the DAIS processors and/or BCIUs, and interrupt the PMC PDP-11/40. The PMC software will set up the SCADU for real-time operation by loading the SCADU control RAMs with specific microprogrammed monitor and control actions.

(6) Set up and control the bus monitor to record or breakpoint on specific multiplex data bus messages.

(7) Display, print or log for the post run editor data collected from the bus monitor or DAIS processors via the CIU and SCADU.

(8) Provide capability to examine or modify DAIS processor registers and memory locations either with absolute or symbolic addresses.

(9) Provide interactive capability with the DEC-10 to set up and run the simulation models.

5.2 Simulated Subsystem Data Formatter System

The Simulated Subsystem Data Formatter (SSDF) software initializes the simulation interface between the host computing complex and the DAIS core elements. The SSDF software is resident in a PDP 11/40 computer and supports the system simulation by mapping data from the mission software to the real-time simulation models executing on the DEC-10. The SSDF initializes and controls the URT, double buffers the data received/transmitted via the multiplex data bus, and moves this information through a DMA-10 interface to the simulation models within the DEC 10 complex. Basic throttle and stick control information is transferred from the cockpit through a separate interface to the SSDF program which then formats the information for utilization by the DEC-10 aircraft models. When operating in real-time, the SSDF software performs the following:

(1) Marks the start of each minor cycle when the minor cycle mode command is received.

(2) Initializes the URT to transmit and receive data from alternate buffers in the four port buffer memory each minor cycle.

(3) Moves data in and out of the DEC-10, DMA window from the four port buffer memory.

(4) Sends an interrupt to the DEC-10 simulation models to perform a computation cycle.

(5) Inputs and outputs the CBIS data, converts the data to the proper format, and moves the data to and from the DEC-10 DMA window.

(6) Updates and displays minor cycle, user's selected RT/subaddress messages and error conditions.

(7) Handles mode command interrupts which require SSDF software to configure the URT to respond like a real RT.

(8) Inputs and outputs the TCC stick and keyboard data, converts the data to the proper format, and moves the data to and from the DEC-10 DMA window.

6. EVANS AND SUTHERLAND GRAPHICS SYSTEM

The Evans and Sutherland (E&S) graphics system is used to generate a cockpit out-of-window scene. The out-of-window scene is controlled by the simulation software so that the scene viewed from the cockpit has the correct dynamic orientation to synchronize with the simulated aircraft motion. The graphics interface software transforms aircraft attitude and position data obtained via the DEC-10 DMA window from the simulation software program into a form that can drive the E&S graphics system.

A typical display produced by the E&S graphics system is shown in Figure 4. These visual displays are generated by a stand-alone general purpose interactive computer graphics system which can display smoothly moving pictures of two or three dimensional objects effectively in real-time. The basic components of the system are a DEC PDP-11, and the following manufactured by the Evans and Sutherland Computer Corporation: hardware processing units which perform such functions as rotations, zooming, and perspective; an 8172-point Refresh Buffer; a Picture Generator; a Character Generator; a 21 inch Picture Display; interactive devices; and the software to support the system.

7. HOST COMPUTER SOFTWARE

The Simulation Software is resident in the DEC-10 host simulation processor (Figure 5) and is the real-time simulation of the real world, the aircraft and the avionics sensor suite. The simulation software consists of a simulation executive and scenario generator; and a set of simulation models.

The simulation software is programmed in Fortran. Assembly language is used for modules if timing or language constrains the usage of the module.

The simulation operates by executing computation cycles of 32 times/second. Input/Output data is transferred to and from the PDP-11 processors once each computational cycle.

7.1. Scenario Generator and Simulation Executive

The scenario generator provides the non-real-time interface with the system user during the initialization stages of a simulation run. By means of interactive commands, the user can select the set of models from a library for the mission simulation to be executed. Also, the user has the capability to change the model parameters individually or initialize all the parameters from a pre-defined stored file. During the real-time simulation run, the user can inspect any of the simulation parameters.

The simulation executive executes the selected simulation models in real-time and operates under the DEC-10 operating system. Input and output parameters from the simulation models are passed to the DEC-10 DMA window for the SSDF PDP-11.

The scenario generator includes the capability to specify model parameters to be recorded during a real-time simulation run. The parameters, along with a time-tag, are recorded on a tape which can be processed by the post run editor.

Also, the simulator includes the capability to record the complete state of the models at a PMC specified breakpoint. This snapshot point is used to restart the models, along with mission software, for repeated testing or demonstration from a specific point in the mission profile.

7.2. Simulation Models

A set of models has been developed which represent various components of the real world simulations. The models include earth model, dynamic air frame model, weapon stores models, sensor/subsystem models, target or IP models, environmental models and weapon scoring model to perform the missions.

7.3. Post Run Editor

The Post Run Editor (PRE) performs, the final phase of testing, the data reduction and analysis for the support facility for both real-time and non-real-time simulation data. The post run editor provides an interactive interface with an operator to define the variable to be analyzed, the analysis routines and the form of data presentation.

The input to the post run editor is Rough Output Tapes (ROTs) containing the data from various sources. This includes inputs from simulation runs collected by the PMC software, SSDF software, cockpit, and the simulation models. Data collected is user identifiable and is time-tagged with major/minor cycle to enable PRE to relate system behavior from the various data sources.

8.0 Future Efforts

To increase the flexibility of the Simulation Support System, three hardware developments are needed. With the advent of bus structured avionic systems, a multiplex universal simulation terminal is needed to provide the capability of controller, monitor and multiple remote terminals. Such a device would allow integration of systems and subsystems without reliance upon any specific architecture. Another tool required for the system is a generalized control and display unit. This piece of instrumentation would provide the capability of monitoring and controlling different airborne processors developed by different manufacturers. A generalized test station which would provide the basic pilot interface is also required so as to permit avionic system architecture evaluations without a specific cockpit system implementation. This Simulation Support System and the planned enhancements provide the Air Force with a full complement of simulation and integration support capabilities needed to support the spectrum of design and integration activities for modern avionics systems.

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Trainor, W.L. and Weber, J.G.; AVSAIL: A Simulation and Support Laboratory for Digital Avionics System Integration and Verification. AIAA 2nd Digital Avionics Systems Conference, Nov. 2-4, 1977.

Maher, R.A.: Digital Simulation: A Dynamic Tool for Development and Operational Support of Aeronautical Systems Software. Proceedings of the Aeronautical Systems Software Workshop, 2, 3, 4 April 1974, Dayton, Ohio.

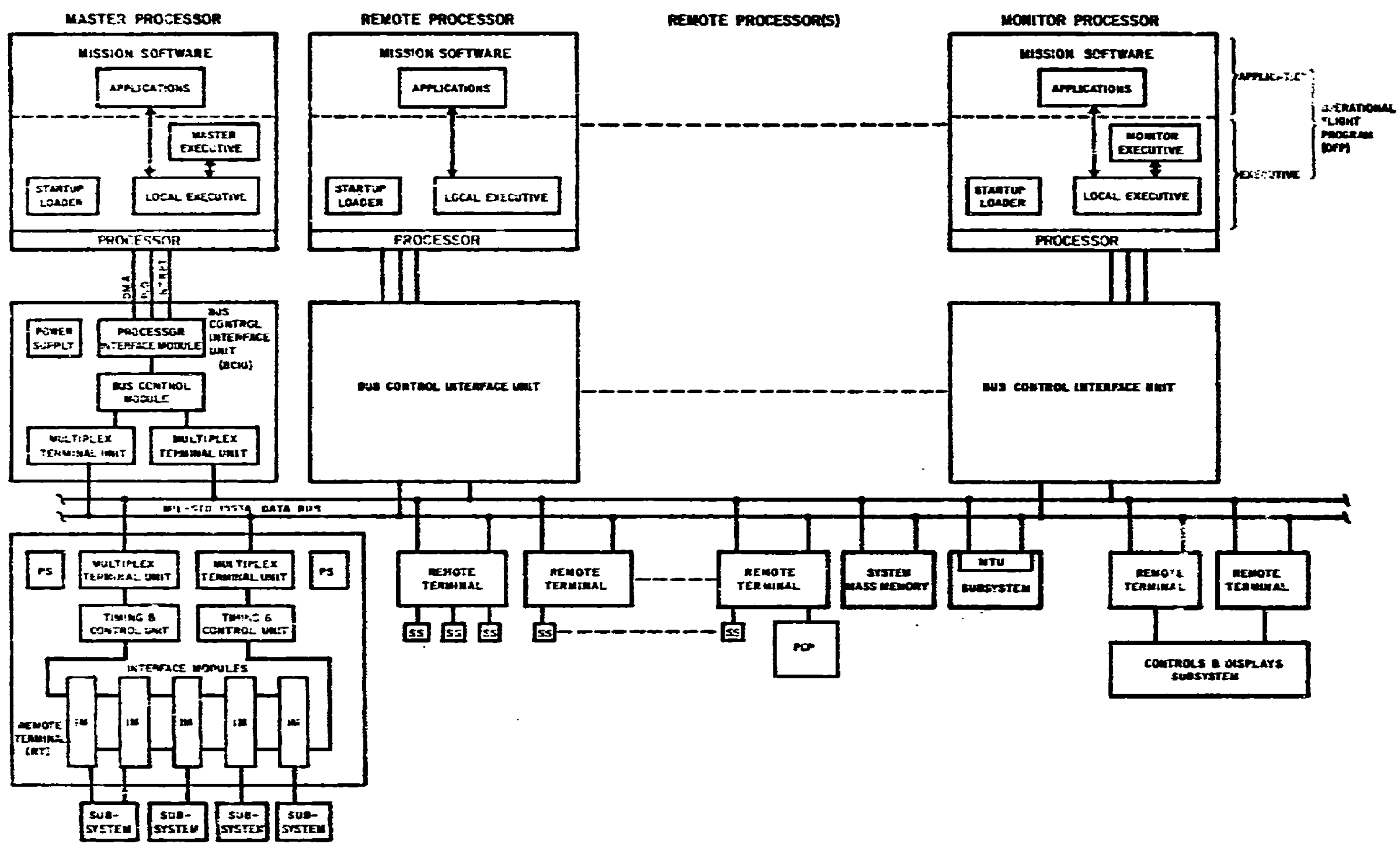


Fig.1 DAIS system architecture

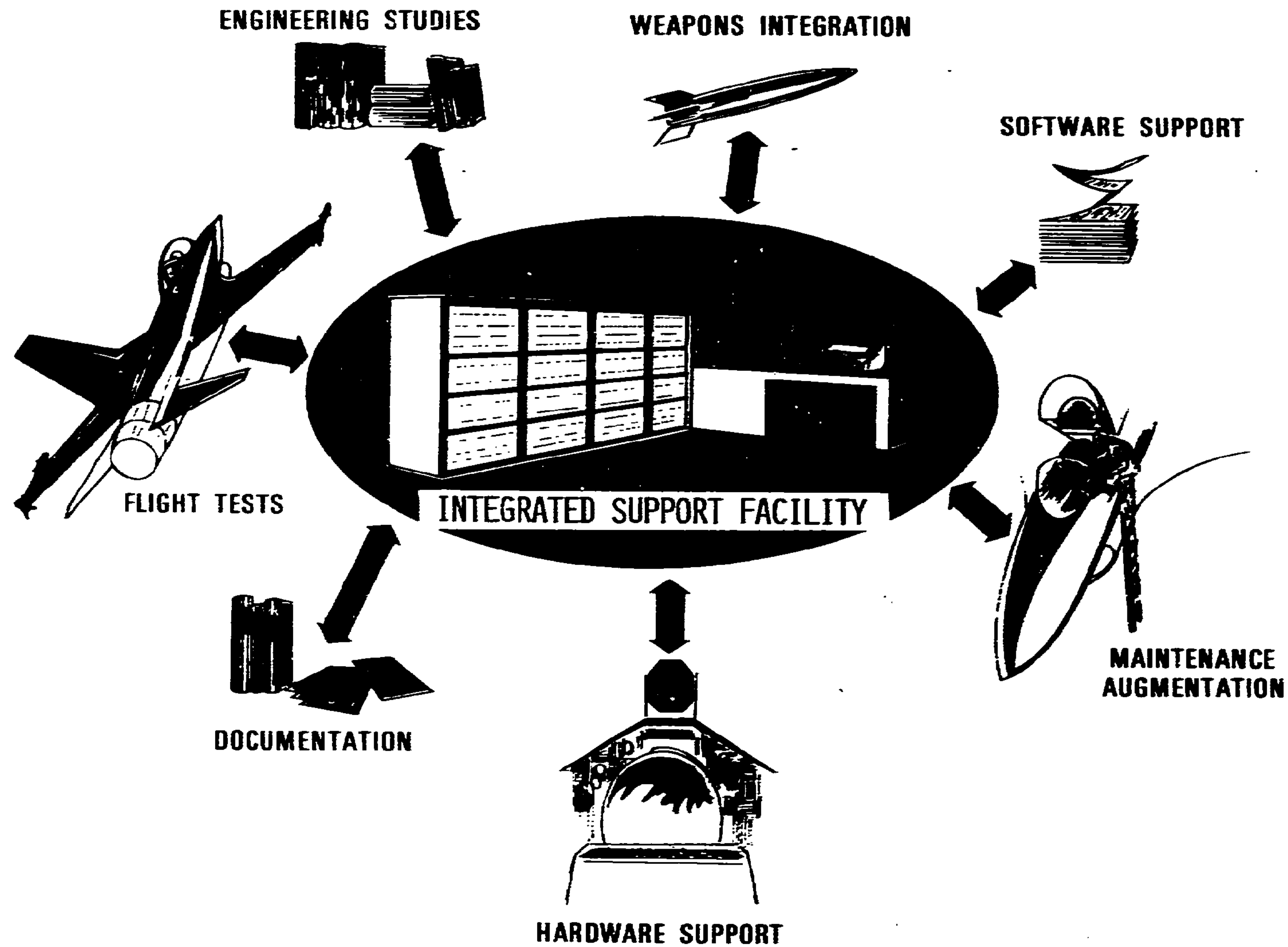


Fig.2 Avionics system development tool

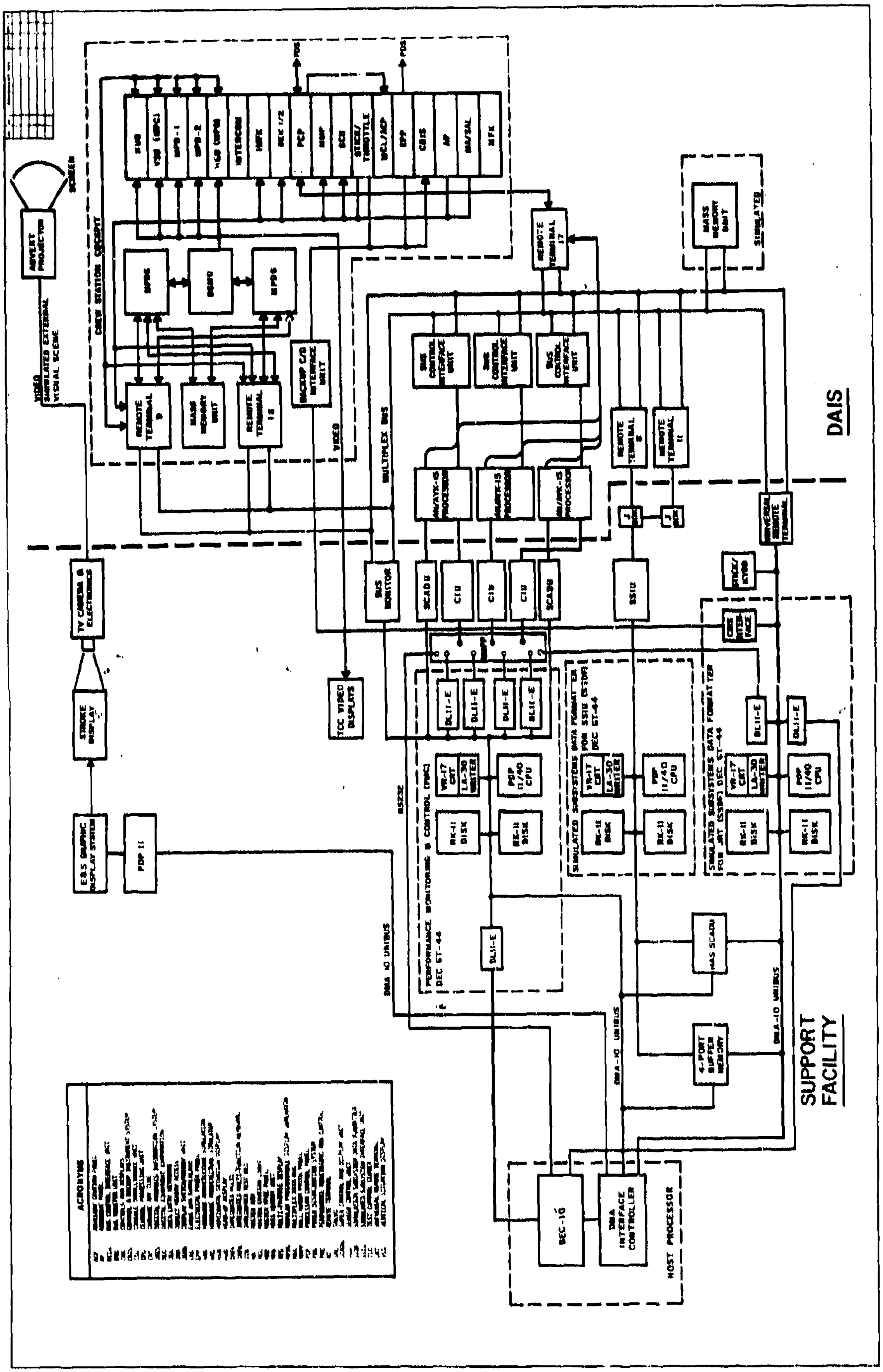

DAIS
SUPPORT FACILITY
HOST PROCESSOR
DEC-10
DMA INTERFACE CONTROLLER
4-PORT BUFFER MEMORY
MULTIPLEX BUS
CREW STATION COCKPIT
SIMULATED
BUS MONITOR
TCC VIDEO DISPLAYS
TV CAMERA & ELECTRONICS
STROKE DISPLAY
PDP 11
ACRONYMS

Figure 3

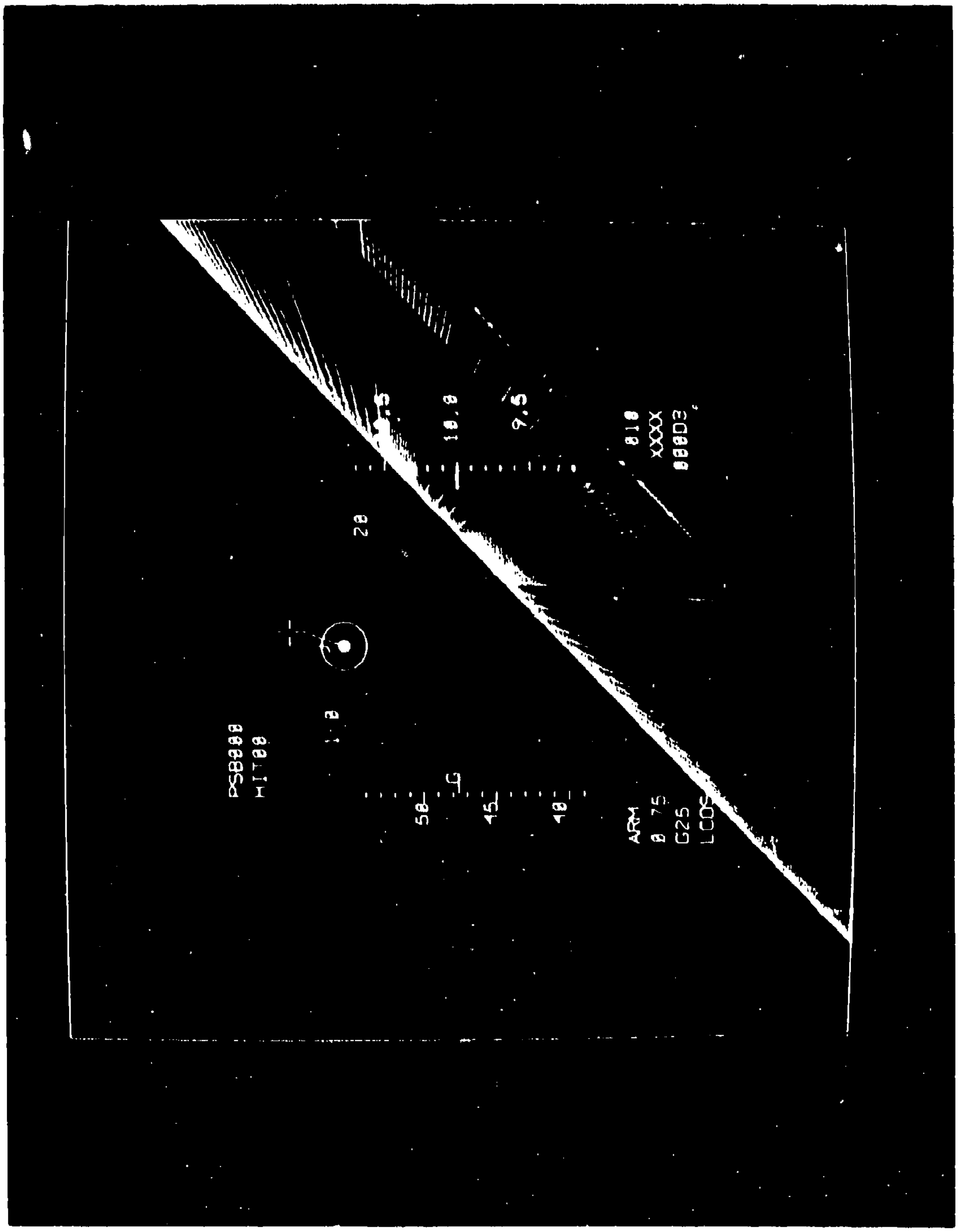


Figure 4

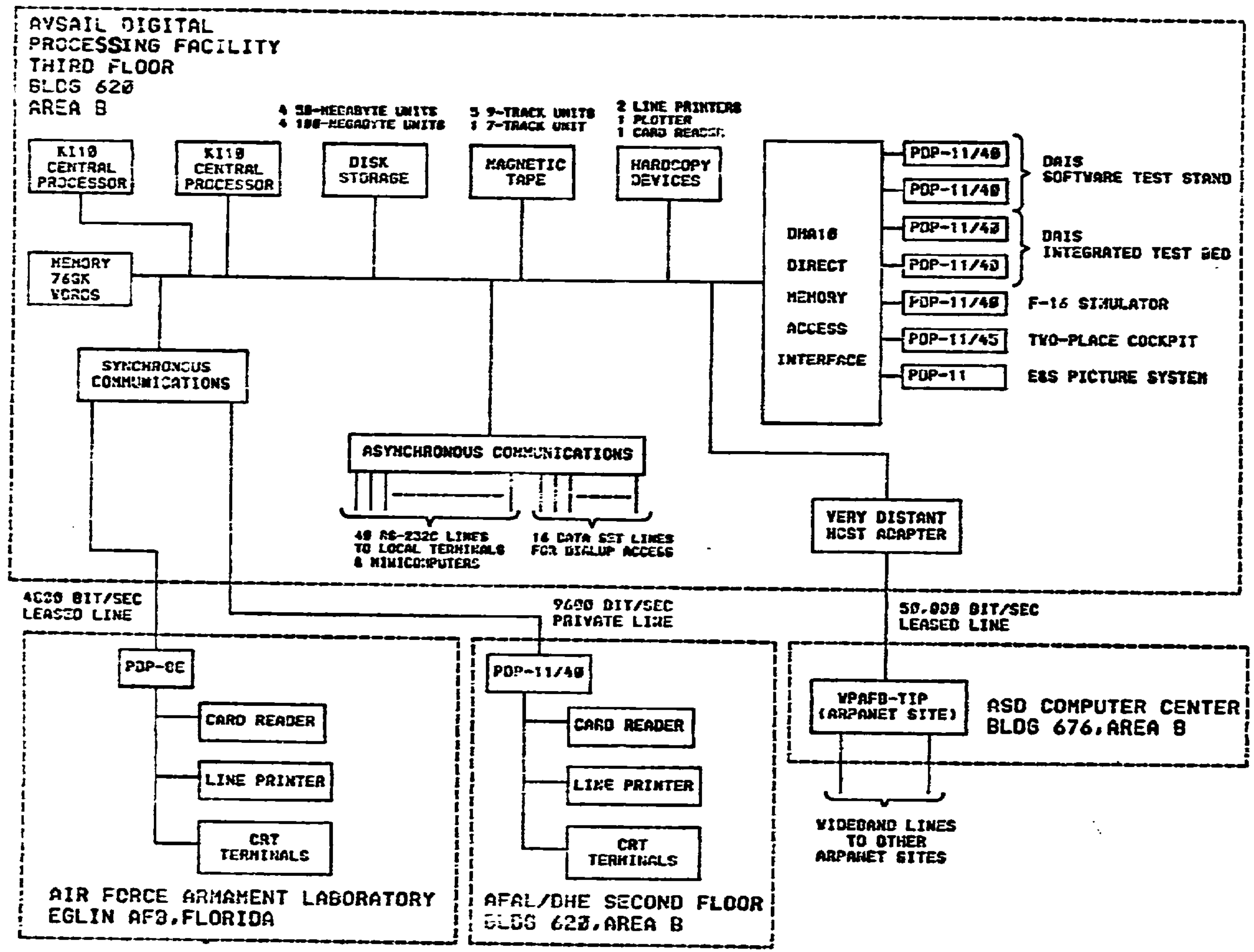


Fig.5 DEC-10 host simulation processor configuration

FIRE CONTROL FOR AIR-TO-AIR GUNNERY IN HIGH PERFORMANCE FIGHTER AIRCRAFT

by

Dipl.-Ing. Hans W. Pongratz
Industrieanlagen-Betriebsgesellschaft mbH.,
8012 Ottobrunn, Germany

SUMMARY

The paper gives a short survey on new aspects in air-to-air gunnery which were initiated by recent improvements in gun fire control.

Then the simulation models used in the TKF simulation for gun fire control and gun scoring are presented, followed by some considerations on the necessary and the possible detail and accuracy of the implemented models.

1. INTRODUCTION

The introduction of the digital computer and new, more accurate and ECM-resistant monopuls radar sensors with frequency agility give us the possibility to take a new approach to air-to-air gunnery.

The digital computer gives the necessary compute power to install more accurate ballistic models, elaborate Kalman filters and other signal-processing features and more elaborate fire control computations.

In applications like AFTI, F-18, and TKF, all or some of these features have been included and thoroughly tested.

The net effect of these improvements in fire control can be an increase of the effective gun range from the 1000-to-2000-ft. to the 3000-to-5000-foot region for a 20 mm gun. A 27 mm gun with its shorter bullet time of flight can reach a still greater range.

This increase in range provides new tactical capabilities like a true head-on capability and possibly an all-aspect capability with the guns.

Furthermore this increase in range closes the gap between maximum gun range and minimum missile range and results in a greater kill probability on close ranges than a missile usually has in this range.

Developing and validating the full potential of these improvements in fire control for air-to-air gunnery require a manned simulation on a simulator providing a realistic target.

In a manned simulation the loop from target image (optical and radar), fire control system, head-up display, pilot, aircraft, gun and ballistics to the score can be defined, developed and evaluated.

For example, the information display for the pilot in the head-up display can be optimized, or a fuselage aiming mode can be tested under realistic air combat conditions.

In these areas, IABG conducts comprehensive simulation work within the scope of the TKF project.

2. AVIONICS SIMULATION MODELS FOR AIR-TO-AIR GUNNERY

2.1 INTRODUCTION

In our simulation work on air combat with the F-104, F-4F, F-106, F-15 performance class aircraft and the TKF, a set of simulation models and programs for air-to-air gunnery has been developed.

In developing these programs, we made some interesting experiences which seemed to repeat themselves whenever we started a new program.

Whenever there is the possibility to solve a mathematical problem either in a closed-solution one-step approach or in an iterative process, the latter usully is more economical in compute time and often easier to install than the former.

Real-time programs should be structured and written from the first line for real-time operation. It usually proves very difficult to convert batch programs into efficient real-time programs and it takes more time than rewriting them completely.

Real-time programs should be written in a modular structure to keep them flexible and transpartent.

When we can write either a deterministic or a describing (stochastic) model, the latter tends to take less compute time, while the former gives us the necessary insight into the system.

In the following paragraphs, some features of the sensor model, a short description of the gun fire control system, and the scoring model implemented in the TKF study, are discussed.

2.2 OUTLINE OF THE REQUIRED SENSOR MODEL

In applications like AFTI and TKF, all the aiming of the gun is done by the fire-control system. So the angle-tracking accuracy of the sensor becomes very important. In the following only a radar sensor will be considered.

For close-in ranges, the biggest angular tracking error is induced by glint. This mainly disturbes the velocity and acceleration outputs of the Kalman filters.

These velocity and acceleration errors also make the biggest contribution to the overall error budget of the lead-angle computation. Therefore glint effects have to be simulated very carefully. A deterministic glint model which represents the target by a number of backscatterers and computes the resulting return signal, would be highly desirable, especially against hard-maneuvering targets, where effective glint magnitude and bandwidth can be affected by target rotational movements.

But this still requires more computing time than can be spent within a complex simulation. So a stochastic glint model is the remaining choice where calibrated noise is added to target position in an antenna coordinate system. The tracking dynamics of the antenna and the break lock of the antenna also must be simulated.

A monopuls radar with frequency agility over a sufficient bandwidth and with a pulse repetition frequency of a least serveral kHz must be chosen to get the desired angle-tracking accuracy.

The readouts of the radar are azimuth angle, elevation angle and range,measured in antenna coordinates. The readouts are fed into the Kalman filter. To save computation time, filtering is done in the geodetic coordinate system. In the real aircraft, another coordinate system may be necessary due to available data inputs, data rate limitations induced by frametime, and accuracy limitations induced by limited word length in on-board computers.

The readouts of the Kalman filter are geodetic position, velocity and acceleration of target, and steering commands for the radar antenna.

Own-ship inertial navigation and airdata and Kalman filter readouts are fed into the fire control computation.

2.3 GUN FIRE CONTROL COMPUTATION MODEL

2.3.1 FUNCTIONS

The fire control computation performs several functions:

- compute bullet time of flight
- extrapolate target flight path until collision
- compute commanded gun barrel line for firing
- compute aiming pipper position in head-up display
- compute in-range conditions

The fire control system is a director sight system, i.e. all informations on the target are based on the radar sensor.

2.3.2 BULLET TIME-OF-FLIGHT COMPUTATION

The bullet time-of-flight compuation and compuation of bullet gravity drop are based on the shooting tables of the ammunition used. The actual velocity time history for the given conditions of launch velocity, altitudes of launcher and target, and mach number are approximated by two constant deceleration sections. The four parameters of

this model are adjusted to the launch conditions by correction functions (App. A 2.2.1).

This velocity time history can be integrated directly up to the measured radar range, giving the first approximation for the bullet time of flight (App. A 2.2.2).

In a second step, the target velocity along the line of sight is taken into consideration to get a better estimate of the lenght of the bullet flight path. (App. A 2.2.3)

Then the target velocity normal to line of sight is included, which already provides a relative accurate bullet time-of-flight estimate (App. A 2.2.4). Now the whole bullet time-of-flight computation is repeated with the last estimate of the flight path length as the starting value.

The accuracy of this procedure is good enough to meet the accuracy of the shooting tables. The bullet time of flight is limited to 4 seconds.

2.3.3 EXTRAPOLATION OF TARGET FLIGHT PATH TO COLLISION POINT AND COMPUTATION OF DESIRED GUN POINTING VECTOR

The extrapolation algorithm uses the position of the target in geodetic coordinates from the Kalman filter and the bullet time of flight as inputs. (App. A 2.3)

To improve the effectiveness of extrapolation, the gradients of the target accelerations in a target-based coordinate system are computed and included into the extrapolation algorithm.

Then the target position at impact is extrapolated in a few integration steps. This allows to take into consideration movements of the target from its original plane, such as barrel roll motions.

These combined features result in an improved firing capability against targets that do evasive maneuvers.

From the target impact position, own-ship velocity vector, gravity drop vector and medium bullet velocity we compute the desired gun pointing vector.

2.3.4 COMPUTATION OF AIMING PIPPER POSITION IN THE HUD

The computed target impact point is the sum of the gun pointing vector times the medium bullet velocity plus the gravity drop vector plus the own-ship velocity vector. (App. A 2.4).

When the extrapolated target flight path vector until impact is subtracted from this value, we get the position of the aiming pipper in geodetic coordinates. The line of sight from the attacker to this point defines the pipper position in the HUD coordinate system.

2.3.5 IN-RANGE COMPUTATION

Maximum gun range is limited by two factors. The impact velocity at the target must be above a certain value to trigger the fuze, and the terminal velocity of the bullet must be still supersonic, otherwise the bullet becomes unstable.

The first limitation governs the tail chase cases, the second the head-on cases.

The actual shooting ranges may be much shortes due to dispersion, and evasive maneuvers of the target.

2.4 SCORING MODEL

2.4.1 INTRODUCTION

First the necessary detail in a gun fire scoring model is discussed.

The vulnerable area of an average fighter plane from the front or rear is about 3 m^2. Exactly from the side, this goes up to about 20 m^2 and from above or below it amounts to about 60 m^2. So there is a factor of twenty in the exposed target area.

Furthermore the kill probability of a single round, given a hit, can vary more than ten to one depending on its impact point and angle, and the caliber used.

When there are multiple hits on the same area, the bullets at the end of the salvo have a lower kill probability than the ones at the beginning. So a sort of saturation effect must be taken into account.

All these effects combined can produce misleading results, if the actual shape, size and kill probability distribution is not used for scoring. Some of these effects but not all of them can be levelled out by an excessive number of runs. So a scoring model should go into considerable detail to avoid these pitfalls.

2.3.2 COMPUTATION OF MISS DISTANCE

Miss distance is computed mainly to give a measure of accuracy of the fire-control system in the real environment. (App. B 2.1)

To reduce the storage requirements of the program in the fire control subroutine, the extrapolated collision point is computed and stored in a ring together with the bullet flight path vector at this point and the bullet impact time.

The miss distance then is defined as the vertical distance of the target center of gravity from the bullet-relative flight path vector at the extrapolated collision point. Because of the long frame time of 50 millisec, the target position at collision time must be interpolated from the frame time values.

The relative flight path vector or impact velocity vector (App. B 2.3) must be taken instead of the geodetic flight path vector to account for the relative motion of the target and salvo at the moment of passing. In this way the computation produces the smallest miss distance actually occurring independently of the time of passing.

2.4.3 COMPUTATION OF HIT PROBABILITY

The hit probability is computed for every frametime from the actual target flight path and attitude, and the actual gun firing data.

2.4.3.1 TARGET MODEL

The target is represented by a simplified model which approximates the shape and dimensions of the actual target projection into a plane perpendicular to the impact velocity vector.

The model area is composed of some ten to thirty subareas. These subareas define the shape and dimensions of the model area. Each of them gets its own capture area and kill probability value.

2.4.3.2 HIT PROBABILITY

Now the average hit probability density for every subarea is computed from the dispersion function. From this, the total hit probability can be added up. (App. B.2).

2.4.3.3 KILL PROBABILITY

By multiplying the individual hit probability of every subarea with its single shot kill probability, and by computing the weighted total, we get the total kill probability per frame.

3. CONCLUSION

As can be seen from the sensor, fire control and scoring simulation models as used in the TKF study, the complexity of the simulation makes a quantum jump as soon as automatic firing modes are simulated. Expecially when automatic firing modus are compared with manual firing modes there are very exacting requirements on the accuracy and fidelity of a simulation.

The outlined models worked well in the TKF simulation and compared favorably with different studies on other facilities. On the other hand there are still a lot of factors not accounted for, such as special propagation effects and ECM conditions, which could lead to another quantum jump in the complexity of the required simulation models.

But this would require also a quantum jump in compute power, if it had to be done in real time.

APPENDIX A

SENSOR MODEL

RADAR: MONOPULSE
FREQUENCY AGILITY
10 FREQUENCIES (MINIMUM)
20 MHZ SEPARATION
HPRF (10 KHZ)
READOUTS: AZ, EL, RANGE

GLINT MODEL: STOCHASTIC
(NOISE ADDED TO TARGET
POSITION)

ANTENNA: TRACKING DYNAMICS, BREAK
LOCK SIMULATED, READOUTS:
DISTURBED AZ, EL, RANGE

KALMAN FILTER: READOUTS: POSITION
VELOCITY OF TARGET
ACCELERATION
STEERING COMMANDS FOR
RADAR ANTENNA

DIRECTOR SIGHT

1. SENSOR

TYPE:	RADAR
RANGE:	10km PLUS
FIELD OF VIEW:	±70° VERTICAL
(FOR TRACKING)	±60° HORIZONTAL

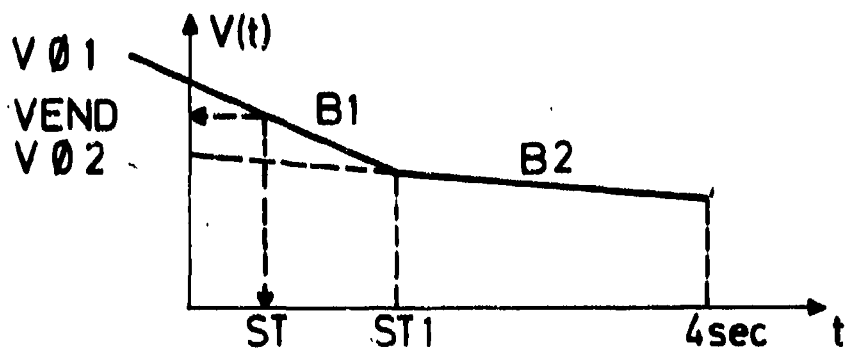
2. LEAD ANGLE COMPUTATION

2.1 GUN RANGE LIMITATIONS

IMPACT VELOCITY (FUZE)
AND BULLET TIME OF FLIGHT
(TERMINAL VELOCITY SUBSONIC
⟶ BULLET UNSTABLE)

2.2 BULLET TIME OF FLIGHT COMPUTATION

2.2.1 VELOCITY-TIME HISTORY IS ADJUSTED TO LAUNCH VELOCITY, ALTITUDE, MACH NUMBER



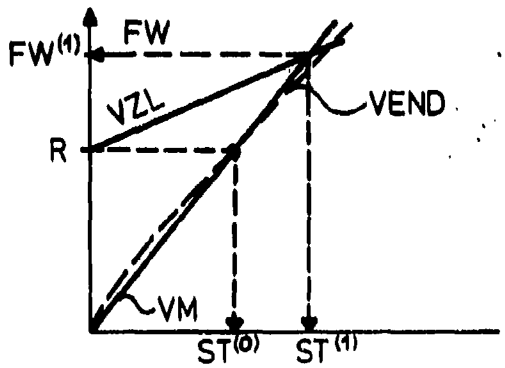
2.2.2 INTEGRATION OF V(t) HISTORY UP TO RADAR RANGE

ST$^{(0)}$=(VØ1-SQRT(VØ1**2-(2.*B1*FW$^{(0)}$)))/B1

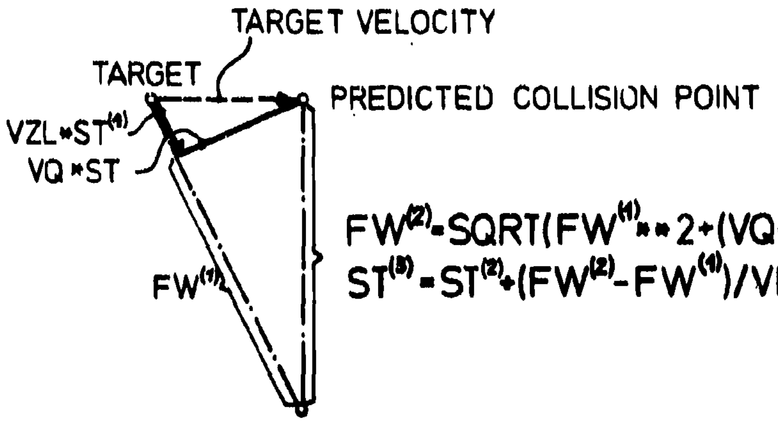
VEND=VØ1-B1*ST

2.2.3 ITERATION INCLUDING CLOSING VELOCITY VZL

ST$^{(1)}$= ST$^{(0)}$+(ST$^{(0)}$*VZL)/(VEND-VZL)



2.2.4 ITERATION INCLUDING TARGET VELOCITY V.Q NORMAL TO LINE OF SIGHT

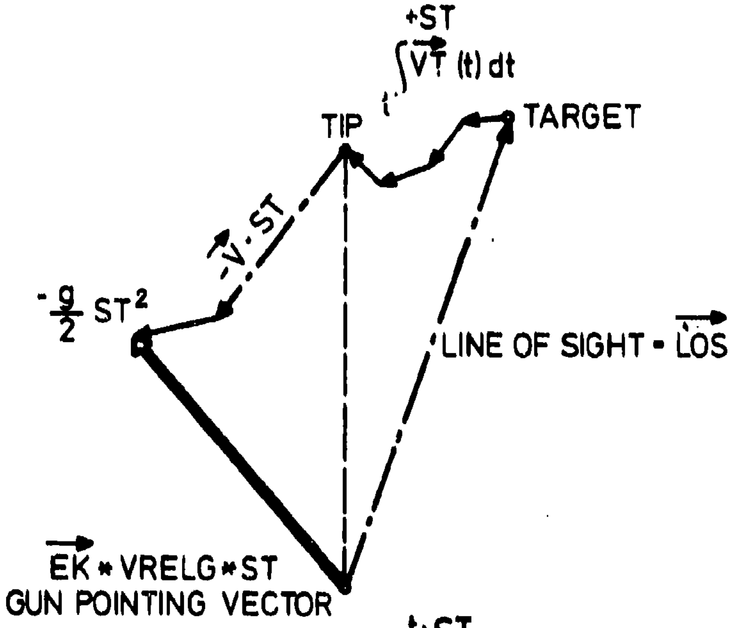


FW$^{(2)}$=SQRT(FW$^{(1)}$**2+(VQ*ST$^{(1)}$)**2)

ST$^{(3)}$=ST$^{(2)}$+(FW$^{(2)}$-FW$^{(1)}$)/VEND

COMPUTATIONS OF 2.2 ARE ITERATED TWICE, FOR RANGES BEYOND MAX. RANGE ST IS SET TO ST MAX.

2.3 COMPUTATION OF DESIRED GUN POINTING VECTOR

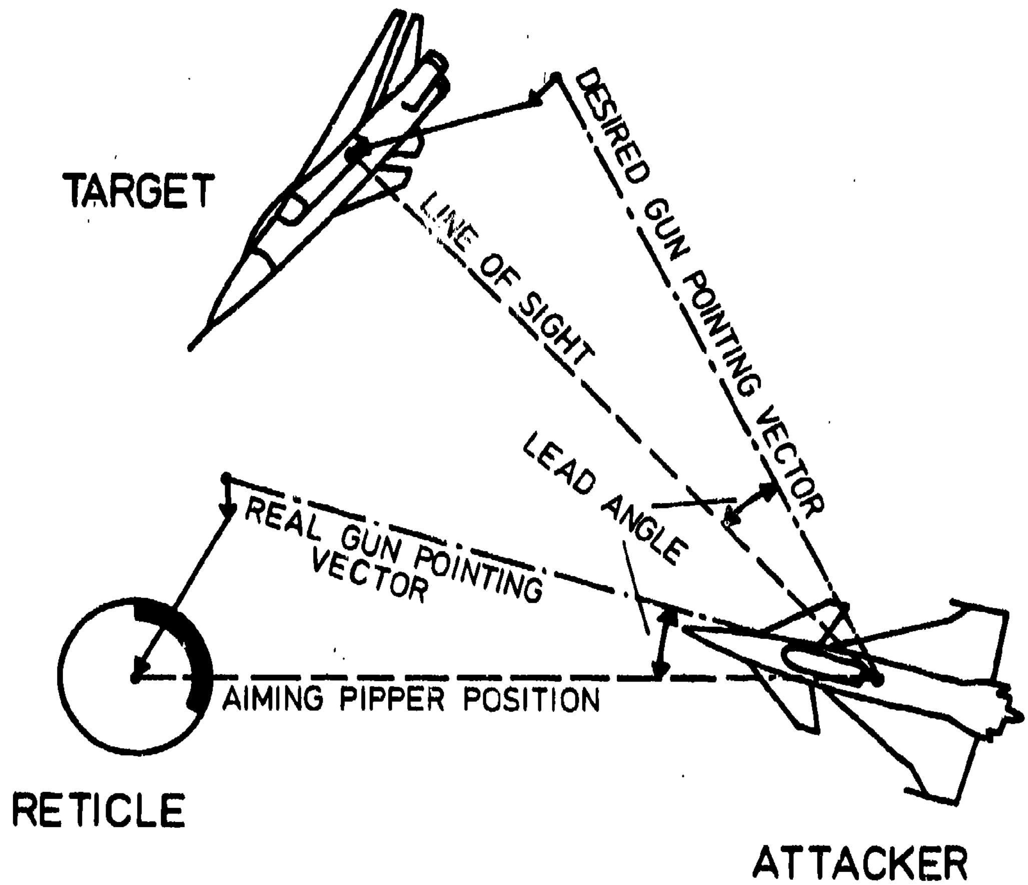


$$EK = \frac{1}{VRELG * ST} * \left(\overrightarrow{LOS} + \int_{t}^{t+ST} \overrightarrow{VT}(t)\,dt - \vec{V} \cdot ST - \vec{G} \cdot \frac{ST^2}{2}\right)$$

COMPUTATION OF TARGET IMPACT POSITION (TIP) INCLUDES GRADIENT OF TARGET ACCELERATION AND BARREL-ROLL MOTIONS OF THE TARGET

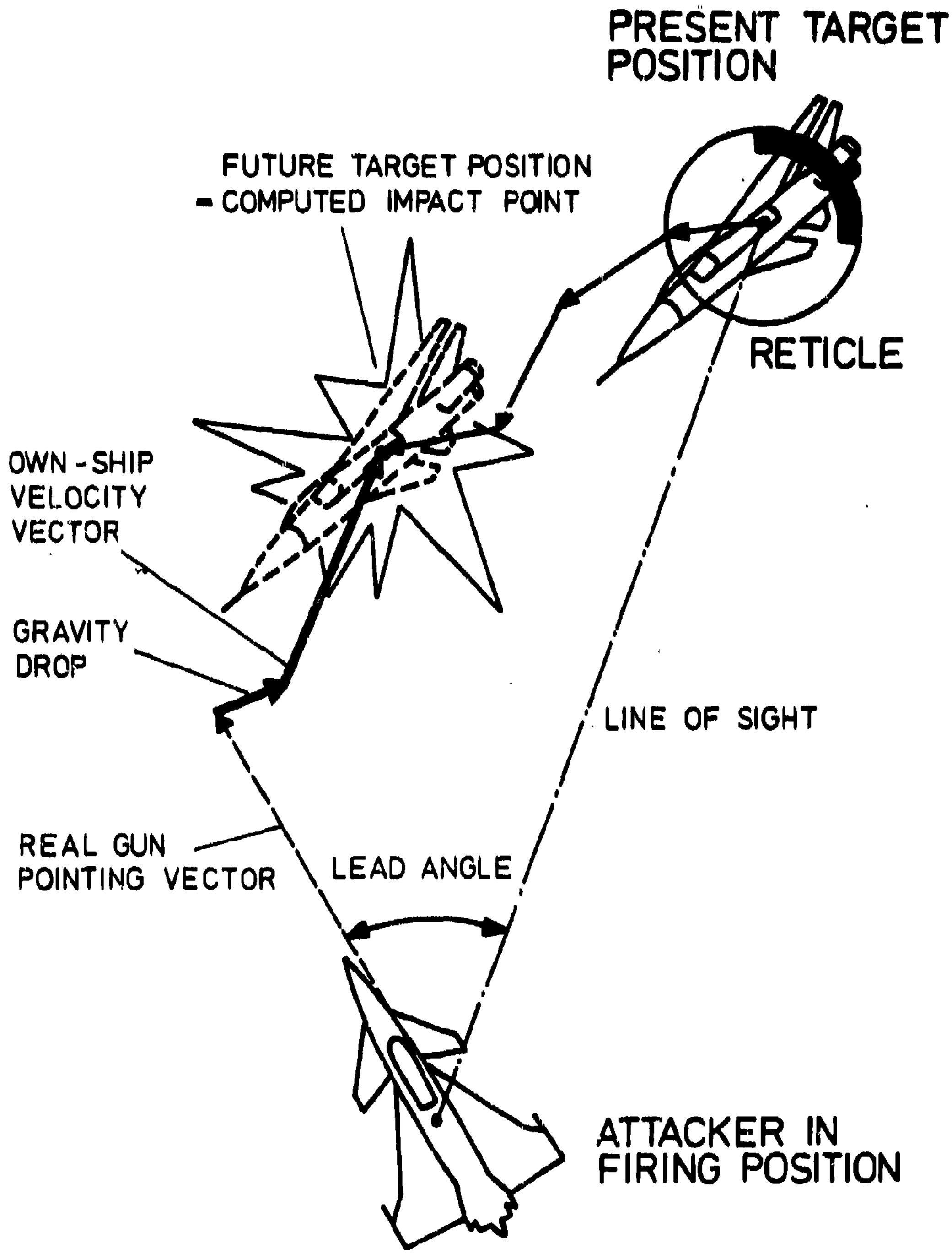
2.4 COMPUTATION OF RETICLE POSITION IN HUD COORDINATES

A) NOT TRACKING



MANEUVER UNTIL RETICLE COINCIDES WITH TARGET

B) EXACT TRACKING
(MANUAL GUN ATTACK)



APPENDIX B

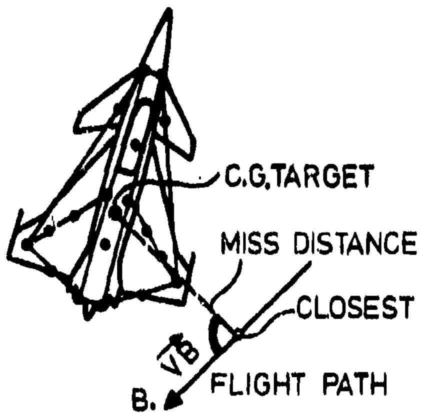
SCORING

1. FIRST A HIT PROBABILITY IS COMPUTED,

THEN A KILL PROBABILITY IS COMPUTED, WHICH INCLUDES A VULNERABILITY MODEL OF THE TARGET

2. METHOD

2.1 TARGET MODEL

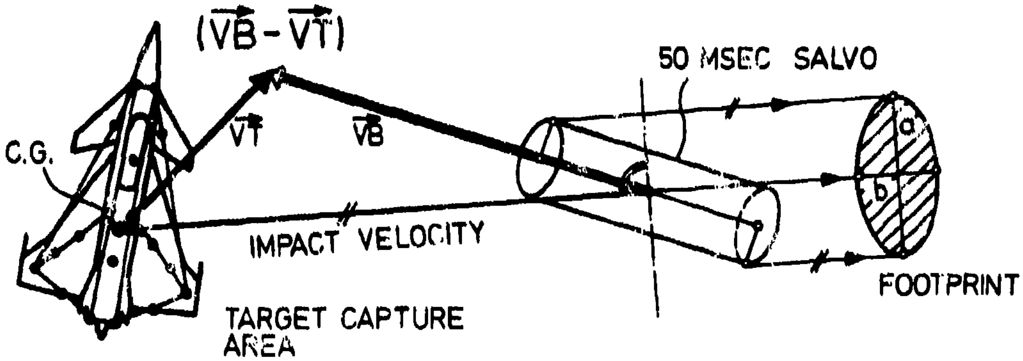


TARGET IMAGE WITH OUTLINE DIMENSIONS OF TARGET (EQUAL AREA)

2.2 COMPUTATION OF MISS DISTANCE

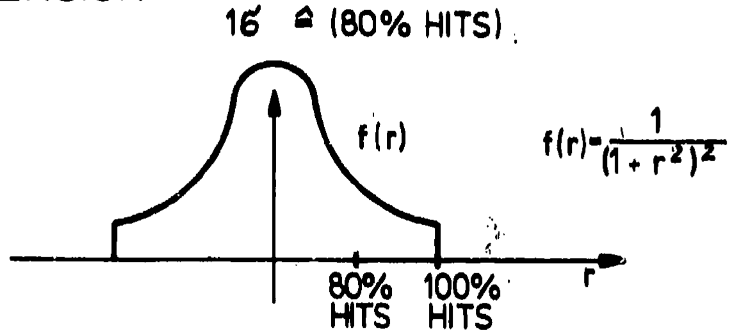
2.3 COMPUTATION OF TARGET CAPTURE AREA

NORMAL TO BULLET IMPACT VELOCITY VECTOR ($\vec{VB} - \vec{VT}$)

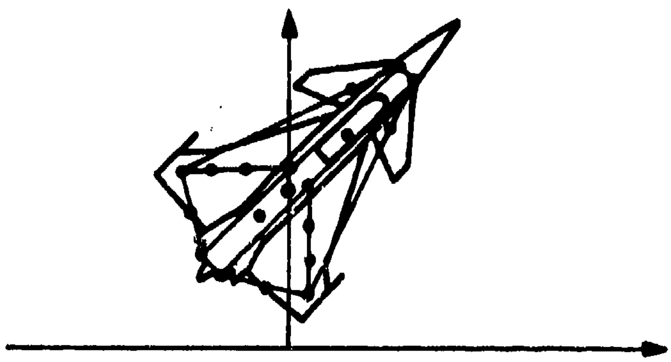


2.4 DISPERSION FUNCTION OF BULLETS IN SALVO

DISPERSION



2.5 INTEGRATION OVER CAPTURE AREA



- OUTLINES OF TARGET IMAGE PROJECTED ON SALVO FOOTPRINT
- COORDINATE TRANSFORMATION TO GET CIRCULAR SALVO FOOTPRINT
- NUMERICAL INTEGRATION OVER 18 MESH POINTS
- LOCATION OF HITS ON TARGET AND ASPECT ANGLE ARE AVAILABLE FOR KILL PROBABILITY COMPUTATION

3. COMPUTATION OF KILL PROBABILITY

- BASED ON A DETAILED VULNERABILITY MODEL KILL PROBABILITY PER FRAME TIME IS COMPUTED
- COMPUTATION INCLUDES:
  - LOCATION OF HITS ON THE TARGET
  - IMPACT ANGLE OF HITS
  - VULNERABILITY OF IMPORTANT TARGET AREAS

SIMULATEUR POUR INTEGRATION

AVEC TESTS DYNAMIQUES DES

LOGICIELS DE CALCULATEURS CENTRAUX EMBARQUES

E. BOUTHORS

ELECTRONIQUE MARCEL DASSAULT

92214 SAINT-CLOUD

RESUME : Il s'agit d'un système conçu pour simuler l'environnement de calculateurs embarqués et fournir les moyens de contrôle permettant la mise au point et la validation des logiciels, avant intégration effective des calculateurs dans l'ensemble des équipements réels environnants.

La caractéristique essentielle du système est de simuler ces équipements environnants, non pas au niveau de leur fonctionnement intrinsèque, mais à celui de leur interface avec le calculateur dans les aspects temporel, interactif et informationnel.

La simulation se fait par fusion d'informations opérateur et d'informations enregistrées sur bande magnétique. Ces dernières simulent les différentes phases de vol envisagées pour les tests tandis que les informations opérateur recréent en temps réel les actions du pilote et les pannes d'équipement.

Des possibilités de fonctionnement en ralenti et pas à pas confèrent une efficacité toute particulière à cette simulation pour la mise au point et la validation des logiciels.

CHAPITRE I

INTRODUCTION

L'ELECTRONIQUE MARCEL DASSAULT (EMD) est spécialisée dans l'étude, le développement et la fabrication d'équipements électroniques de pointe, tant dans le domaine militaire que dans le domaine civil.

L'effectif de l'EMD est de 2.500 personnes, dont 1.400 ingénieurs et cadres. L'informatique aérospatiale (calculateurs, bus numériques, systèmes digitaux, logiciels de base et d'application) constitue une des activités principales de l'ELECTRONIQUE MARCEL DASSAULT : 20 à 25 % du chiffre d'affaires est réalisé dans ce domaine.

Depuis 1965, époque à laquelle l'EMD a conçu le premier calculateur embarqué européen utilisant des circuits intégrés, les missiles balistiques français sont équipés de calculateurs universels EMD, puis EMD-SAGEM à la suite d'accords de coopération signés entre les deux sociétés.

En 1976, l'accroissement des besoins en matière de puissance de calcul conduit l'EMD à promouvoir en France de nouvelles technologies de composants et de circuits pour créer une nouvelle génération de calculateurs universels :

- 1084 pour missiles balistiques,
- M182 pour avions MIRAGE F1,
- 2084 pour avions MIRAGE 2000.

Le système de transmission des informations numériques à bord de ces avions a lui aussi été développé par EMD : c'est le bus numérique GINA (DIGIBUS).

L'EMD réalise également tous les logiciels de base et, sous la maîtrise d'oeuvre de ses clients, la plupart des logiciels d'application concernant ses propres calculateurs aérospatiaux. L'introduction de la nouvelle génération de calculateurs EMD en tant que calculateurs principaux des avions MIRAGE F1 et MIRAGE 2000 développe considérablement cette activité logiciel.

Les logiciels, dans les applications avioniques, ont présenté deux caractéristiques : d'une part, un volume et une complexité très importants , d'autre part, la nécessité de livrer ces logiciels temps réel sans disposer en usine d'un système complet pour la mise au point et la validation.

Pour faire face à ces nouvelles contraintes, les efforts ont porté dans deux directions :

- l'emploi d'une méthodologie de développement très rigoureuse qui a fait l'objet d'une communication au symposium AGARD de OTTAWA en Mai 1979 (exposé 53),

- le développement d'outils de tests et de validation. Ces outils ayant pour but de permettre la fourniture de logiciels de très grande qualité grâce à leur mise en oeuvre préalable dans un environnement simulé.

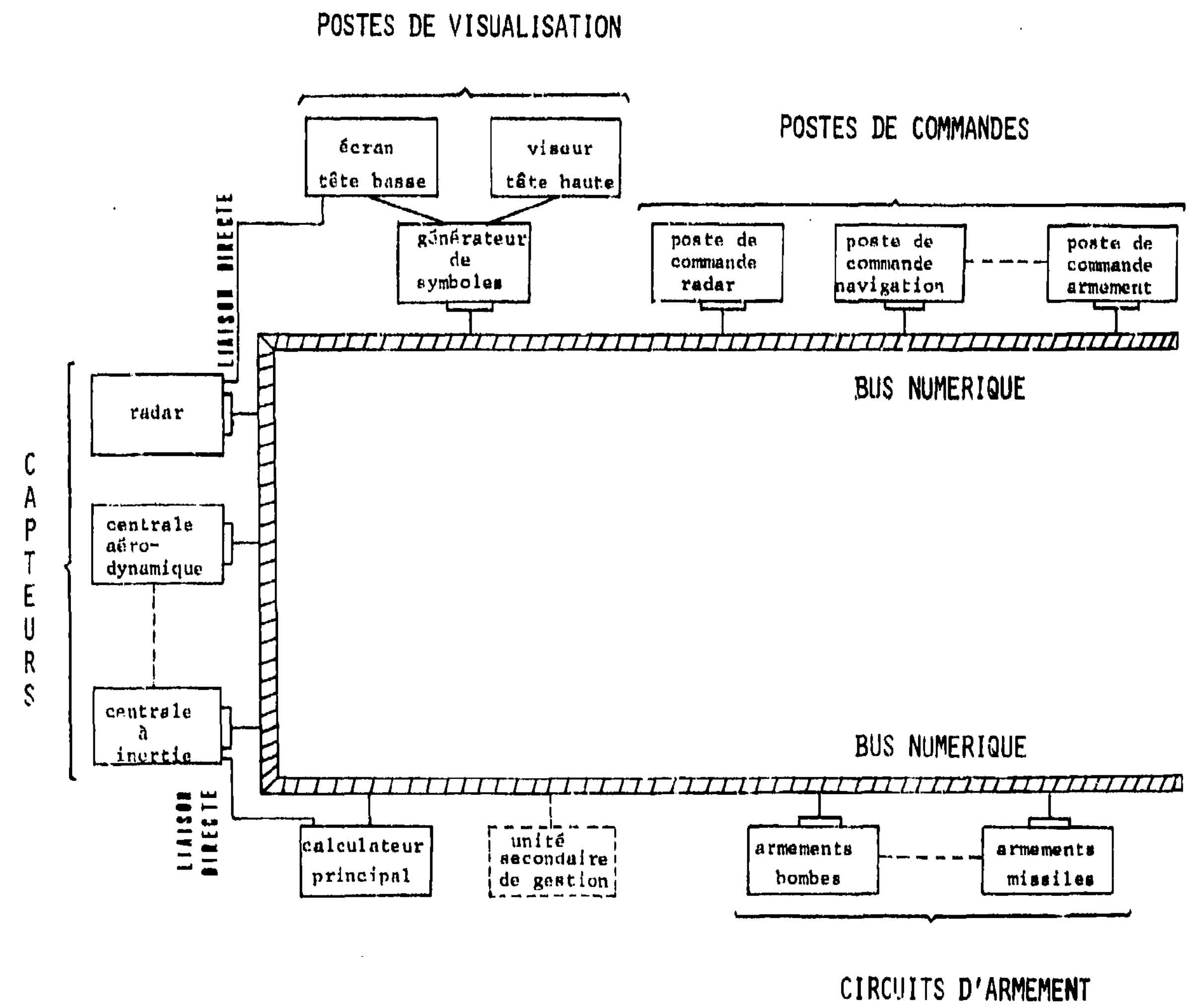
Avant de décrire la simulation de cet environnement, il est nécessaire d'en préciser le contexte ; d'une part, les fonctions du calculateur principal dans un système d'armes avionique, d'autre part, les contraintes de réalisation d'un outil de tests dynamiques et de validation.

CHAPITRE II

CONTEXTE DE LA REALISATION DES SYSTEMES DE SIMULATION

2.1. FONCTIONS DU CALCULATEUR PRINCIPAL DANS UN SYSTEME D'ARMES AVIONIQUE

Le système de navigation et d'attaque (SNA) d'un avion de combat moderne peut être très schématiquement illustré, dans son principe général, par la figure suivante :



Parmi les principaux équipements du SNA, on distingue :

- des capteurs : centrale à inertie, centrale hydrodynamique, radar, etc...
- des postes de visualisation : écran tête basse, viseur tête-haute, etc...
- des postes de commande : pour la navigation, l'armement, le radar, etc...
- des circuits d'armements : pour bombes, canons, missiles, etc...

Bien que tous ces équipements comportent une part de plus en plus grande d'électronique numérique, c'est-à-dire de processeurs spécialisés et très intégrés au matériel, les calculs effectués y sont de nature différente de ceux du calculateur principal : ils sont spécifiques de l'équipement, contribuent directement à ses performances et ne traitent généralement que des données locales.

Au contraire, le logiciel du calculateur principal intervient au niveau global du système de façon relativement indépendante des caractéristiques particulières des équipements. Il assure deux types de fonctions :

- des fonctions de gestion centralisée (échanges d'information, surveillance du fonctionnement d'ensemble) :

  Le schéma fait apparaître le rôle particulier du bus numérique ou "digibus" auquel sont connectés la plupart des équipements du système d'armes. Les informations échangées entre ces équipements transitent sur cette liaison sous forme numérique et suivant un mode de multiplexage temporel à haute fréquence. Les liaisons directes entre équipements sont de plus en plus rares : il en subsiste encore quelques unes pour différentes raisons (survivance de techniques analogiques, débit d'informations, sécurité).

  La gestion du bus numérique est assurée par le calculateur principal. Le système peut aussi être équipé d'une unité secondaire (USG) qui gère le bus en cas de défaillance du calculateur principal.

- des fonctions opérationnelles : à partir des données élaborées par les capteurs et des ordres introduits manuellement sur les postes de commandes par le pilote, le calculateur principal effectue un certain nombre de traitements permettant d'assurer les missions opérationnelles de l'avion : navigation, attaque Air-Sol, attaque Air-Air; suivant la mission, certains résultats de calculs sont adressés à des équipements comme les circuits d'armement, d'autres informations sont présentées au pilote sur les postes de visualisation. Dans quelques cas, une partie de ces traitements est effectuée par des calculateurs implantés dans le radar ou le viseur par exemple. L'unité de gestion secondaire (USG) assure certaines de ces fonctions opérationnelles et joue ainsi le rôle d'un deuxième calculateur principal.

2.2. CONTRAINTES DE LA REALISATION D'UN OUTIL DE TESTS DYNAMIQUES ET DE VALIDATION

- La contrainte essentielle est le délai qui est encore plus court que pour le logiciel embarqué. D'une part, les spécifications (matériel logiciel) ne sont réalisables que lorsque celles du système avionique sont terminées, d'autre part, l'outil doit être disponible avant le début des tests dynamiques du logiciel embarqué.

- Le coût ou l'état de développement des équipements réels du système rend ces derniers indisponibles chez le fabricant de logiciel .

- Enfin, le coût du matériel impose une certaine standardisation des moyens de tests entre les différents projets.

CHAPITRE III

L'OUTIL DE SIMULATION POUR L'INTEGRATION ET LA VALIDATION

DES LOGICIELS EMBARQUES : LA BAIE DE VALIDATION DE LOGICIEL

L'outil développé par EMD pour l'intégration et la validation des logiciels embarqués porte le nom de "Baie de Validation de Logiciel". Par la suite, il sera représenté par son sigle : BVL.

3.1. OBJECTIFS

. Il s'agit d'abord de mettre au point des fonctions complètes et de les tester dans leur configuration temps réel.
Cette phase de mise au point vient après la phase de tests statiques qui a permis de vérifier la partie algorithmique du logiciel. Pour ces tests, il est nécessaire de se doter de moyens d'investigation plus élaborés que les moyens classiques.

. Les logiciels livrés doivent être en conformité avec les clauses techniques qui sont appelées "spécifications détaillées du logiciel". Cette conformité est assurée grâce aux opérations de validation. Pour valider, il faut donc fournir au logiciel des informations conformes à celles décrites dans les spécifications détaillées du logiciel. D'autre part, il faut avoir des possibilités de visualisation pour s'assurer de la conformité des résultats obtenus.

. Les opérations décrites ci-dessus doivent être réalisées par le fabricant de logiciel de manière autonome, c'est-à-dire que le logiciel ne doit pas être tributaire du développement ou de la disponibilité des autres équipements du système avionique. Par ailleurs, il serait mauvais de monopoliser le banc d'intégration de l'avion pour la mise au point du logiciel.

3.2. PRINCIPES GENERAUX

. Le grand principe de base est de faire exécuter, en usine, le logiciel opérationnel dans un calculateur embarqué réel.
Les contraintes qui en résultent sont les suivantes :
- tous les moyens de contrôle et d'investigation doivent être extérieurs au logiciel opérationnel.
- l'environnement simulé du calculateur doit refléter fidèlement l'environnement opérationnel.
- les chronogrammes d'exécution et d'échanges d'information doivent être aussi proches que possible des conditions opérationnelles.

. Il ne faut pas perdre de vue qu'il s'agit de mise au point de la validation de logiciel. Lors de l'analyse de l'environnement à simuler, il ne faut donc pas s'attacher au fonctionnement de chaque équipement mais à ses relations avec le logiciel à valider.

. Enfin, l'outil devra être commode et simple d'emploi, en particulier, il n'est pas recherché une corrélation automatique avec des résultats pré-enregistrés. La validation est assurée par l'opérateur qui a la possibilité d'adapter en permanence le niveau de contrôle, du plus global au plus fin.

3.3. SOLUTIONS ADOPTEES

a) Simulation des informations en entrée

Le bilan des informations amène à les classer en deux types :

- informations issues de capteurs et liées à la marche de l'avion (UNI, CAé,...).
- informations aléatoires issues d'équipements ou de commandes pilote (postes de commande, états de pannes...).

L'ensemble de ces deux types d'informations est à restituer de manière dynamique et cohérente avec leur format réel.

Un fichier séquentiel (bande de vol) contenant les informations "capteurs" est créé en centre de calcul. Les informations aléatoires sont générées en temps réel sur la baie de vadilation du logiciel par simulation des postes de commande et des mots d'états d'équipements.

b) Contrôle du déroulement du logiciel

Le contrôle du déroulement du logiciel est fait directement par action sur le matériel du calculateur embarqué.

Ce contrôle par le matériel permet donc d'arrêter le calculateur sans affecter l'aspect temps réel.

L'échelle de temps élémentaire du système (le cycle court = 20 ms) constitue l'élément de base de la simulation. Cette possibilité permet d'arrêter le processus (édition de résultats, observation) et de le reprendre en séquence. En particulier, il faut noter la possibilité de fonctionner au ralenti ou au pas à pas.

c) Moyens d'observation

Deux types d'observation sont mis à la disposition de l'opérateur :

- contrôle par écran

  L'avantage de ce dispositif est de pouvoir surveiller l'évolution des paramètres en temps réel. L'opérateur peut définir les informations qu'il souhaite voir sur l'écran grâce à un programme conversationnel. Le contrôle peut être réalisé au niveau global par observation des phénomènes tels que les voient les utilisateurs opérationnels (viseur simulé, poste de commande simulé).

  Le contrôle peut également se situer au niveau des interfaces d'entrée/sorties que l'opérateur peut visualiser.

  Enfin, le système permet d'observer des informations internes qui n'ont pas d'existence physique au niveau des interfaces. En particulier, une liste de contenus mémoire peut être observée en permanence.

- contrôle par imprimante

  L'opérateur définit en conversationnel les informations et le format qu'il souhaite éditer. Deux possibilités s'offrent à lui :

  - déclencher une impression au moment qui semble opportun et redémarrer en séquence.
  - déclencher une impression automatique à des instants précis consignés dans une table initialisée par l'opérateur au début du travail.

3.4. DESCRIPTION DU MATERIEL COMPOSANT LA BAIE DE VALIDATION DE LOGICIEL

La configuration matérielle a pour objet de :

- transmettre au calculateur-avion les informations sous les formes prévues en fonctionnement opérationnel.
- permettre les actions-opérateurs simulant les actions-pilotes.
- permettre la visualisation et l'impression de paramètres et résultats.
- permettre la mise en oeuvre de la BVL.

On peut distinguer quatre parties :

a) le calculateur de baie, qui est un calculateur EMD série 84, équipé de 64 K mots de mémoire, et qui réalise tous les traitements de simulation non effectués au centre de calcul (génération du fichier bande magnétique).

b) les périphériques de mise en oeuvre de la baie :
- une imprimante avec entrée/sortie sur cassette permettant le fonctionnement hors temps réel, en particulier les initialisations , ainsi que le chargement de programmes.
- un lecteur de ruban perforé permettant le chargement des programmes et de la mémoire de l'écran.
- une face-avant permettant la simulation d'états et le dépannage de la baie.

c) Les périphériques de simulation de l'environnement-avion .
- un ensemble écran graphique avec clavier alphanumérique, clavier-fonction et crayon de désignation de l'écran. Cet ensemble permet la simulation des différents postes de commandes, des viseurs, des discrets et pannes, les affichages des paramètres, et le fonctionnement en modes ralenti ou pas à pas.
- un dérouleur de bande magnétique permettant l'exploitation séquentielle du fichier de paramètres généré en centre de calcul.
- un manche aux axes permettant la génération de trajectoires.

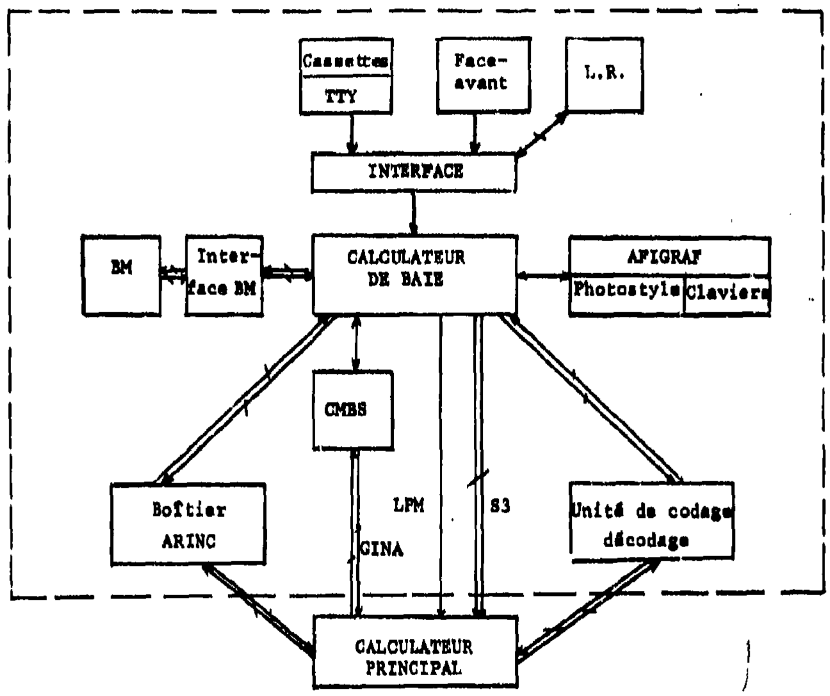
d) les périphériques de liaison avec le calculateur central embarqué.
- un ensemble coupleur multimode du bus standard (CMBS) et digibus qui sert à l'échange des données numériques, et qui permet la simulation de tous les abonnés au digibus dont le calculateur avion est gérant.
- une unité de codage décodage qui simule les synchros, les tensions ainsi que les discrets "fil à fil".
- un ensemble de mise en oeuvre du calculateur avion, comprenant un bus parallèle 16 bits et une ligne série de procédure et de maintenance.
- un coupleur pour simulation d'informations sur bus ARINC.

Remarques :

On peut ajouter d'autres coupleurs de liaisons pour simulation de liaisons particulières à un type d'avion.

L'imprimante sert aussi à l'impression des paramètres.

Le dérouleur de bande magnétique sert aussi au chargement des programmes dans la BVL et dans le calculateur-avion.



3.5. <u>DESCRIPTION DES LOGICIELS NECESSAIRES AU FONCTIONNEMENT DE LA BAIE DE VALIDATION DE LOGICIEL</u>

a) <u>Logiciel de génération du fichier bande magnétique</u>

La génération du fichier bande magnétique se fait en deux parties : tout d'abord génération de paramètres primaires, puis traitement complémentaire et mise au format pour générer les "bandes de vols".

La génération des paramètres primaires se fait de deux manières : en centre de calcul ou sur BVL.

- en centre de calcul , l'utilisateur définit une trajectoire par points de consignes, en donnant le vecteur vitesse pour chaque point, et en définissant les conditions initiales du vol, telles que : hauteur du sol, latitude, longitude et wander angle initiaux, composantes du vent, déclinaison magnétique, position et vecteur vitesse des hostiles, coordonnées et type de but.. Ces données initiales sont stockées en tête du fichier bande magnétique.

  La trajectoire de consigne est ensuite filtrée de manière à ne pas affecter sa forme générale. En tenant compte d'un modèle de la terre et d'un modèle d'atmosphère, sont générés alors les paramètres primaires dont les principaux sont : la position courante de l'avion, la vitesse de l'avion en axes géographiques, les sinus et cosinus des roulis, tangage et cap vrai, l'incidence, l'erreur de route, les valeurs accélérométriques... Ce logiciel est écrit en FORTRAN sur IBM 370.

- sur BVL, la trajectoire est générée en temps réel. Cette méthode présente par rapport à la précédente les avantages suivants :
  . sélection/désélection des buts au choix,
  . réponse à une loi quelconque de pilotage,
  . possibilité par relecture de la bande en ralenti de vérifier instantanément la qualité du vol.

  Ce logiciel génère les mêmes paramètres que le précédent . Il nécessite en outre des modules de gestion de l'imprimante, de l'écran graphique, des claviers, du manche-2-axes et du dérouleur de bande magnétique. Il est écrit partiellement en LTR, l'autre partie étant en assembleur.

La génération des paramètres secondaires est réalisée en centre de calcul en reprennant le fichier primaire créé par une des méthodes décrites ci-dessus. Ce logiciel est directement lié au type de l'avion.

On complète par les principaux paramètres suivants :
- centrale aéro : températures statique et totale, Mach, vitesse conventionnelle, densité de l'air, altitudes barométriques et réelle...
- centrale à inertie : rayons de courbure locaux est et nord, incréments en latitude et longitude, variations du wander angle, vitesses et accélérations en axes plateforme, écart de route...
- système radar : site, gisement, élévation de la cible, vitesses relatives, distance cible, rotations en axes avion de la droite avion-cible...

Ce logiciel est écrit en FORTRAN sur IBM 370. Sa sortie est la bande de vol exploité sur BVL lors de la phase de tests dynamiques. Il permet la génération de paramètres cohérents.

b) <u>Logiciel de simulation et de test</u> :

Il est séparé en trois groupes :
- le logiciel de base
- le logiciel de baie
- le logiciel de simulation

Le logiciel de base : il s'agit là d'un logiciel indépendant de la BVL, servant à d'autres applications sur d'autres matériel. Il se compose de deux parties :
- le système qui est le programme de mise en oeuvre des baies et calculateur de la série 84. Il assure trois fonctions :
  . fonction "pupitre" de gestion de la face avant de la baie.
  . fonction système d'enchaînement des travaux (en conversationnel ou par lots).
  . fonction surpervision d'entrées/sorties pour les programmes s'exécutant dans le calculateur-avion ou dans le calculatur de baie.
- le moniteur temps réel, qui est un produit compatible LTR et Assembleur 84. Ses fonctions sont :
  . la gestion des tâches
  . la gestion des événements
  . la gestion des ressources
  . la gestion des entrées/sorties
  . le partage du temps

  C'est le moniteur temps réel qui contrôle tout le logiciel BVL. Il est à noter que c'est un moniteur identique qui supervise le logiciel du calculateur-avion. Il est paramètré de manière à adapter le volume de ses tables de chaque application.

L'ensemble du logiciel de base de la BVL représente un volume mémoire de 12 K mots de 16 bits.

Le logiciel de baie : c'est le logiciel spécifique BVL qui est indépendant de l'application au niveau du code. Il s'agit des programmes suivants :

. gestion des interruptions : ces modules ont pour principales fonctions :
  - d'acquitter les demandes des divers périphériques (bande magnétique, coupleur multimode de bus standard, écran cathodique, télétype), afin d'élire les diverses tâches requises.
  - de cadencer à l'aide d'une horloge programmable les travaux cycliques.
  - gérer les erreurs de niveau élevé : erreurs de parité, débordement flottant...

. gestion de la bande magnétique : elle réalise l'acquisition des divers paramètres permettant de simuler un vol, et de réaliser l'enregistrement des valeurs lors de la génération de trajectoires synthétique "au manche".

. gestion des échanges : il s'agit du traitement des entrées/sorties vis-à-vis du calculateur-avion, c'est-à-dire l'émission/réception des discrets "fil à fil", des codages et décodages, et du dialogue sur le digibus via le CMBS.

. gestion de l'écran graphique : elle comprend l'ensemble des programmes réalisant le décodage des commandes clavier ou photostyle et le branchement du traitement correspondant, et l'affichage à l'écran des différentes images avec leur rafraîchissement cyclique.

. gestion télétype : elle permet le dump sur télétype d'un ensemble de variables lues en mémoire du calculateur-avion, définies par leurs labels rangés en table , avec format, mise en page, MSB... Elle réalise l'impression automatique ou interactive de ces paramètres.

L'ensemble du logiciel de baie représente un volume mémoire de 10 K mots de 16 bits.

Le logiciel de simulation : il comprend d'une part le logiciel image de l'écran, d'autre part, le logiciel-calculateur de baie.

. le logiciel image de l'écran constitue en fait la partie graphique de la simulation. Il s'agit des représentations des différents équipements dont on simule l'interface, des affichages de paramètres et de pannes.
  Ce logiciel constitue par secteurs la mémoire de l'écran, et représente environ 10 K mots de volume mémoire. Il est écrit dans un langage interprétatif en centre de calcul.

. le logiciel de simulation comprend en fait la logique de traitement de toutes les informations en entrée/sortie du calculateur-avion. A cela, il convient d'ajouter toutes les logiques nécessaires pour l'élaboration des diverses informations. Pour certaines simulations, ce logiciel atteint 30 K mots.

CHAPITRE IV

CONCLUSIONS ET PERSPECTIVES

La baie de validation du logiciel a montré qu'il est possible, dans le domaine avionique, de valider un logiciel temps réel en dehors du contexte opérationnel réel.

Pour améliorer la productivité de la BVL, il est possible de tenter une automatisation de la procédure de validation par comparaison des résultats à des valeurs pré-enregistrées. Cette option est difficile à retenir par le manque de souplesse qui la caractérise.

Le problème fondamental de qualité réside dans l'inadéquation des spécifications de logiciel avec le problème à résoudre et les modifications du logiciel qui en découlent. C'est donc dans le domaine de l'établissement des spécifications que doivent se porter les efforts.

CRUISE-MISSILE-CARRIER NAVIGATION REQUIREMENTS

George T. Schmidt and Roy H. Setterlund

Guidance and Navigation Advanced Programs Division
Advanced Systems Department
The Charles Stark Draper Laboratory, Inc.
Cambridge, MA, U.S.A. 02139

ABSTRACT

This paper addresses the modeling, simulation, and performance predictions used in determining aircraft avionics and transfer-alignment requirements for a generic aircraft that would launch cruise missiles over water, a considerable distance from a first TERCOM update area. Such would be the case for an undefended wide-body aircraft that must remain far away from an opponent's air defense system. This long standoff range presents some unique requirements that are not present in a mission where cruise missiles are launched "close" to the first fix point, as from a penetrating bomber. The methodology used and system requirements results are described.

1. INTRODUCTION

During the past year, the Air Force has been considering several existing U.S. aircraft as possible cruise-missile (CM) carriers. These aircraft range from small military transport aircraft to large wide-body commercial aircraft.[1] This paper describes the methodology and results of a parametric study conducted to determine the navigation requirements for such aircraft.

Section 2 of this paper describes the methodology used in allocating the allowable navigation errors between the CM guidance system and the cruise-missile-carrier-aircraft (CMCA) avionics system. From this baseline error allocation, avionics and transfer-alignment tradeoff studies were conducted. These tradeoff studies are described in Sections 3 and 4, respectively. In Section 5, a total weapon-system evaluation from aircraft takeoff to CM impact is presented which validates the error allocation of Section 2.

2. METHODOLOGY FOR BASELINE SYSTEM ERROR ALLOCATION

To initiate the CMCA avionics tradeoff portion of the study, it was necessary to define a baseline mission for both the CMCA and the CM, and to allocate the errors between each navigation system to meet the total required accuracy at the first TERCOM fix area. The baseline mission is summarized in Figure 1.

- BASELINE SUMMARY – AIR START/AIR ALIGN OF CMCA INS
  - CMCA FAST REACTION TAKEOFF FROM CONUS
  - 0.5-hour DEAD RECKONING TO FIRST RADAR FIX
  - 6 EQUALLY SPACED (ΔT ≈ 15 min) OUTBOUND RADAR FIXES (1000 ft. CEP)
  - DOPPLER AIDING OVER LAND, UNAIDED INERTIAL OVER WATER
  - 1 hour 15 min BEFORE LAUNCH, CM INS ACTIVATED
  - 0.5 hour BEFORE LAUNCH, S-TURN TRANSFER ALIGNMENT MANEUVER
  - CM LAUNCH 8 __ hours TO __ hours AFTER LAST OUTBOUND FIX
  - CM FLIGHT (≈ __ nmi) TO LANDFALL TERCOM MAP
  - CM UPDATES VIA ENROUTE MAPS TO TARGET

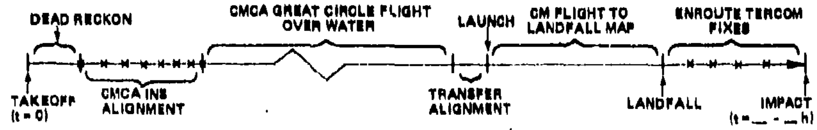


Figure 1. Baseline mission evaluation.

The mission begins with a fast-reaction takeoff from the U.S. with the CMCA inertial-navigation system (INS) dormant and unheated at takeoff. During the next 30 minutes, the attitude heading and reference system and a Doppler radar are used to dead-reckon to the nominal site of the first radar position fix while the CMCA INS is being powered up and thermally stabilized. Near that first radar fix, the CMCA INS is initialized from the dead-reckoning system and then begins navigating after the fix has been made. Nominally, a total of eight equally spaced radar fixes are made during the overland portion of the outbound flight so that the CMCA INS is satisfactorily aligned prior to beginning its long overwater flight to the CM launch area.

During overwater flight, the CM INSs are powered up 45 minutes before transfer alignment and calibration of the CM INSs relative to the CMCA INS are begun. The transfer-alignment/calibration sequence is performed within a 30-minute period prior to launch of the first missile. The assumption is that only one horizontal CMCA maneuver will be used during this 30-minute period to aid the alignment filter. Following completion of transfer-alignment and calibration, the CM is launched while it is still a considerable distance from the first TERCOM fix point. The CM, immediately after launch, descends to a low altitude and executes a maneuver to bring it to its proper course; then it proceeds to navigate to the first landfall map.

The calibration of the CM guidance set is a particularly important aspect of the transfer-alignment mechanization. Figure 2 lists the gyro and accelerometer performance parameters for the CM guidance set after a 2-1/2-year dormancy period.[2] Even if the CM guidance system were provided with perfect initial conditions by the CMCA INS, these performance parameters would result both in a system error growth rate on the order of 16 nmi/h and in a totally unacceptable position error at the nominal first-fix point. (A 0.01-deg/h gyro drift results in about a 1.0-nmi/h error growth rate.) Consequently, the methodology of the study was to first evaluate how well transfer alignment and calibration might be performed; then to allocate the errors between CMCA avionics and transfer alignment; and finally to perform detailed studies within each allocation to determine if the allocations could be met.

The method of assessing the possible accuracy from transfer alignment is to perform a covariance analysis based on a complete 40-state model of the CM navigation-system errors, assuming an error-free CMCA navigation system. Position differences between the two systems are compared and processed in an optimal filter to estimate the CM INS parameters. A full 40-state optimal filter leads to optimistic results since, in practice, only about 10 important error states would be implemented in the CM computer. Consequently, a "consider-variable" approach is used in the analysis which allows a realistic estimate of how a reduced-order filter might perform; this approach alleviates the need to actually design a reduced-order filter.[3,4,5] Figure 3 illustrates the consider-variable approach.*

Parameter	Units	Acceptance Value (1σ)	30-Month Turn-On Value (1σ)
GYRO			
Drift	deg/h	0.02	0.16
Random Drift	deg/h	0.005	0.005
g-sensitivity	deg/h/g	0.05	0.11
Scale-factor error	%	0.05	0.11
g^2-drift	deg/h/g^2	0.02	0.02
Misalignment	$\widehat{sec}$	120	120
ACCELEROMETER			
Bias	μg	500	040
Random bias	μg	10	21
Scale-factor error	%	0.05	0.11
Misalignment	$\widehat{sec}$	60	60

Figure 2. Inertial instrument parameters.

SYSTEM MODEL:	$\underline{x}(t_K) = \Phi\, \underline{x}(t_{K-1}) + \Gamma\, \underline{w}$
MEASUREMENTS:	$\underline{z}(t_K) = H\, \underline{x}(t_K) + \underline{v}$
STATISTICS:	$\mathrm{cov}(\underline{x}(0)) = P(0)$ $\mathrm{cov}(\underline{w}) = Q,\ \mathrm{cov}(\underline{v}) = R$
PROPAGATION:	$P^- = \Phi P^+ \Phi^T + \Gamma Q \Gamma^T$
OPTIMAL GAIN:	$K = P^- H^T (HP^- H^T + R)^{-1}$
SUBOPTIMAL GAIN:	Appropriate rows of gain matrix, corresponding to those states that would not be estimated in the implemented filter, are zeroed. With that modified K, update $P^+ = [I - KH]\, P^- [I - KH]^T + KRK^T$

Figure 3. Consider-variable covariance analysis.

This technique was applied to the transfer-alignment problem. Figure 4 illustrates the results of transfer alignment and calibration performed relative to the assumed-perfect CMCA inertial system while the aircraft was performing a horizontal S-turn maneuver during the transfer-alignment period. Cases 2, 3, and 4 correspond to different measurement noises in the position-match filter used for transfer alignment between the INSs. The measurement noise would be due to local vibrations, bending, and flexure between the INS locations. Case 3, corresponding to a noise of 1-ft rms, would probably

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* Reference 6 contains a typical covariance-analysis program.

exceed the levels to be expected in any of the aircraft considered. Consequently, Case 3, a CM navigation performance of 1.0 nmi/h (CEP) relative to the CMCA INS, was chosen as the baseline performance that should be established as a goal for transfer alignment and calibration of the CM guidance set.

Section 4 will consider the various aspects of transfer alignment and calibration in detail in an attempt to meet the goal of a calibrated CM INS whose errors grow at a rate on the order of 1 nmi/h with respect to the CMCA INS. Figure 4 also illustrates that a key parameter is the azimuth gyro bias term that exists after transfer alignment and calibration have been completed. Case 2 was rerun with a perfect azimuth gyro, and the differences in performance are quite noticeable. In fact, as illustrated in Figure 5, a significant error growth rate appears due to the azimuth gyro alone, if the gyro is uncalibrated. Consequently, for long-range air-to-ground weapons using this guidance system, adequate calibration of the azimuth gyro is required if the 1-nmi/h (CEP) relative error growth rate is to be met.

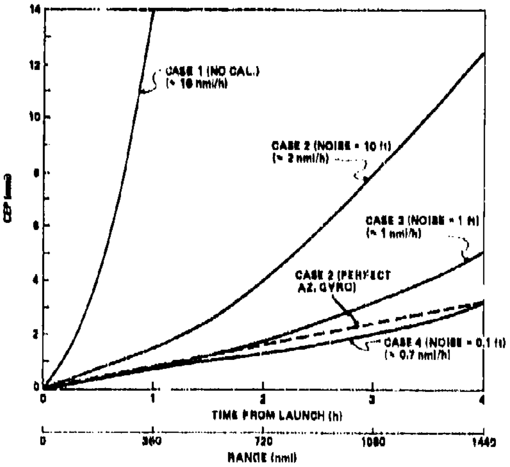

Figure 4. Impact of transfer alignment/ calibration on missile performance.

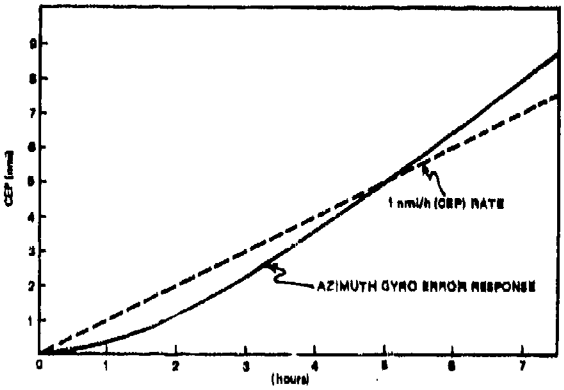

Figure 5. Response to azimuth-gyro bias of 0.1 deg/h (1σ) flying northwest great circle at 600 ft/s constant velocity.

Given the requirements on navigation accuracy (CEP_{LF}) at the first TERCOM map, and using the expected CM INS relative navigation-error-rate performance ($CEPR_{CM}$) of 1 nmi/h and the time the CM must fly to the first map, it is then a simple matter of algebra to determine an approximate expression for the required CMCA navigational accuracy. Equation 1 illustrates the mathematics.

$$CEP_{LF} = \left[CEPR_{CM}^2\,(t_{LF} - t_L)^2 + CEPR_{CMCA}^2\,(t_{LF} - t_{OF})^2\right]^{1/2} \tag{1}$$

where

CEP_{LF} = required CEP (nmi) at first TERCOM fix after CM launch

$CEPR_{CM}$ = relative error growth rate of CM INS (nominally 1 nmi/h)

t_{LF} = time at first TERCOM fix (h)

t_L = time of CM launch (h)

$CEPR_{CMCA}$ = error growth rate of CMCA INS in nmi/h

t_{OF} = time of last position update of CMCA INS (position update is assumed perfect); $t_L - t_{OF}$ is then the overwater time of the CMCA during which there are no updates

From this simple expression, the maximum allowable range of the CM from launch to landfall fix can be traded off against CMCA INS quality for various overwater CMCA flight times (i.e., time since last CMCA position fix); see Figure 6. For the purposes of this

paper, a nominal 0.5-nmi/h (CEP) has been selected for the CMCA navigation system. This performance allows several missile standoff ranges as a function of the overwater flight times. In Section 3, the avionics requirements to achieve that goal are presented.

It should be noted that this study addressed only the position error required to cross the first TERCOM map. No requirements were studied for acceptable downrange or crossrange velocity errors, azimuth errors, etc., at the first map, the assumption being that an acceptable fix could be made if the CM overflew the map.

3. METHODOLOGY OF CMCA AVIONICS TRADEOFFS

To select a set of CMCA avionics meeting the baseline error allocation of 0.5 nmi/h (CEP) after the last CMCA outbound fix, a consider-variable approach was again used. A 12-state subotimal filter consisting of north and east position and velocity errors, three INS attitude errors, three gyro biases, and two Doppler errors was used during the outbound CMCA flight to perform CMCA in-flight alignment and calibration after the cold start of the CMCA INS.

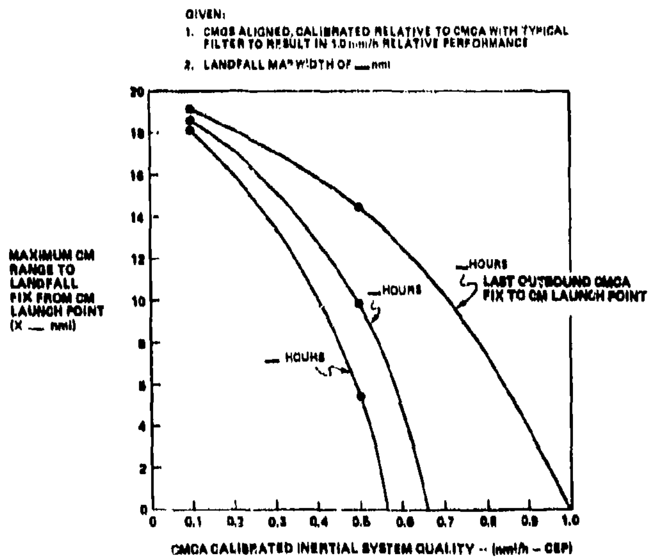

Figure 6. CM range versus CMCA calibrated INS quality for overwater flight times from last CMCA outbound fix.

Using the various avionics suites for the overland outbound CMCA flight, the resultant error propagation for three generic INSs has been plotted in Figures 7 and 8. It should be noted that for the cases employing Doppler aiding, Doppler aiding is shut off after the last outbound fix so that for all cases the INS operates in the pure inertial mode (with the exception of altimeter aiding) during the overwater flight. This avoids having to make modeling assumptions about ocean currents. The cases with Doppler aiding refer to the use of Doppler aiding up to and during the position-fixing portion of the baseline mission.

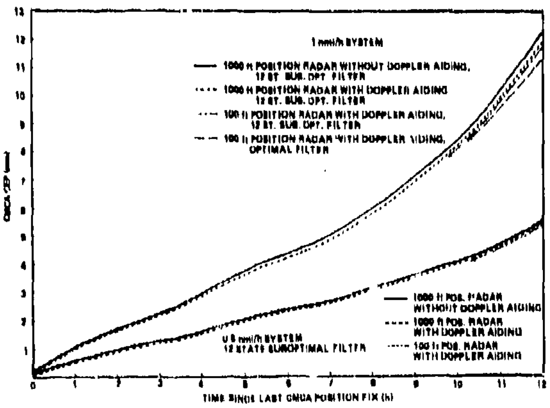

Figure 7. Impact of performance to avionics using baseline fixes (8 fixes).

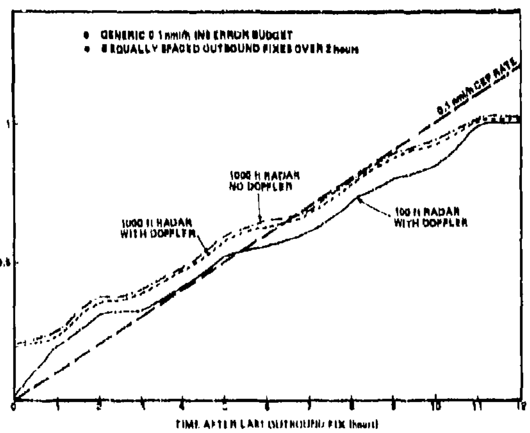

Figure 8. Impact of avionics on baseline mission.

The results presented point to an obvious conclusion that the CMCA performance after the last outbound fix is practically insensitive to improvements in the position-fixing radar and Doppler aiding between fixes for the baseline mission. This insensitivity is due to the fact that even with a moderately accurate position-fixing radar (1,000-ft CEP), eight fixes are enough to estimate the alignment of the platform and to trim the sensor biases to the levels limited by random drifts and nonobservability.

Figures 9 and 10 show the time histories for the calibration of the azimuth error and north gyro bias, respectively, during the outbound CMCA flight using the 0.5-nmi/h-CEP navigator and no Doppler aiding. These plots show that using a higher accuracy radar allows faster calibration and alignment of the platform. However, given a total of eight outbound fixes, the end result remains the same.

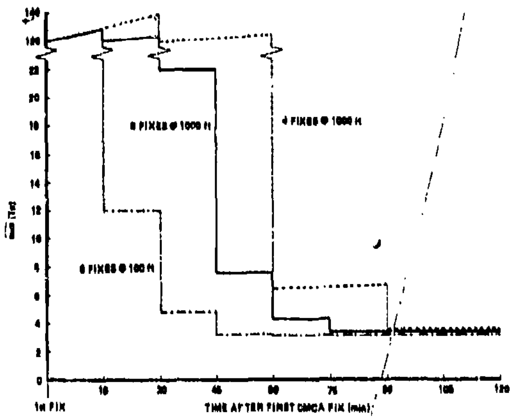

Figure 9. CMCA azimuth error calibration (0.5-nmi/h system).

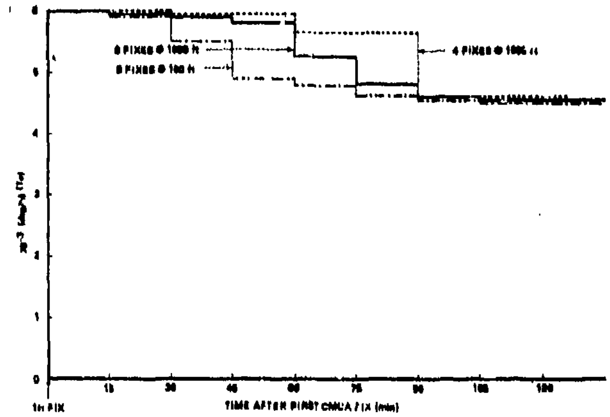

Figure 10. CMCA north-gyro bias calibration (0.5-nmi/h system).

Figure 11 shows the impact of the position-fixing radar accuracy on CMCA performance when the number of equally spaced outbound radar fixes is reduced. The figure charts the CMCA CEP 8 hours after the last outbound fix for the generic 0.5-nmi/h-CEP navigator. Figure 12 is a time history of error propagation when a 2,000-ft-CEP radar is used for outbound position fixing. Note that in both Figures 11 and 12, no Doppler aiding is employed between position fixes. Both figures illustrate the need for more accurate position-fixing radars if the time and number of outbound fixes is reduced from the baseline. It does appear, however, that as long as six outbound fixes are available over a 1-1/2-hour period, adequate CMCA INS alignment can be achieved using a 2,000-ft-CEP radar alone.

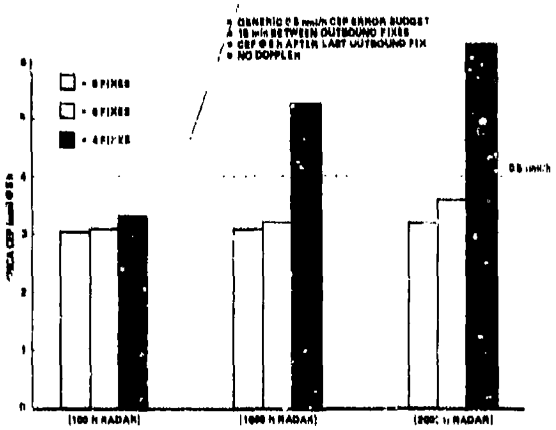

Figure 11. Impact of reducing the number of equally spaced outbound position fixes.

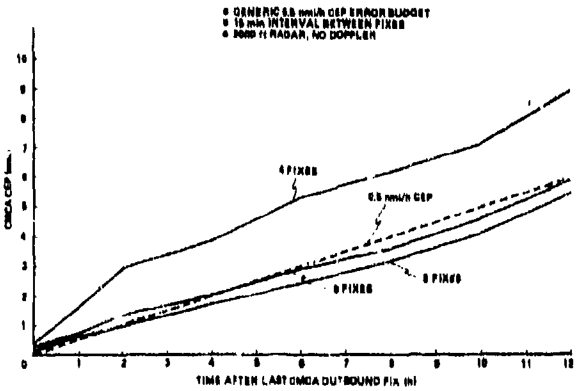

Figure 12. Impact of reducing the number of equally spaced outbound position fixes.

Figure 11 also shows that four outbound fixes using a 1,000- to 2,000-ft-CEP radar are not adequate to align the 0.5-nmi/h INS to the 0.5-nmi/h (CEP) level using only radar fixes. Figure 13 shows that the addition of Doppler aiding between four outbound 2,000-ft radar fixes permits further calibration and alignment of the CMCA INS down to the 0.5-nmi/h (CEP) level. What Doppler aiding provides is best illustrated in Figure 14, which is a plot of azimuth misalignment estimation during the outbound fixes. Doppler aiding enables faster azimuth estimation, so that by the fourth fix, the steady-state estimation level has been reached; whereas without Doppler aiding, two more fixes are required.

Similar results were observed using a better quality 0.1-nmi/h (CEP) navigator. The impact of reducing the time and number of equally spaced outbound fixes for this navigator is shown in Figure 15. Again, the importance of Doppler aiding when the number of fixes is reduced is clearly shown. It is noteworthy, however, that by using the

higher quality navigator, no Doppler aiding, and a 1,000-ft-CEP radar, an acceptable error growth rate of 0.5-nmi/h (CEP) can still be achieved with four fixes. Thus, higher quality navigators provide the flexibility of reducing TERCOM map widths or, as an alternative, may provide for reducing the number of outbound radar fixes, particularly with Doppler aiding in use.

Figure 16 illustrates the required TERCOM landfall map widths versus CMCA INS quality. If the baseline map width is reduced by a factor of 2, then the requirement on the CMCA INS is on the order of 0.2 to 0.3 nmi/h (CEP). There is an advantage to using smaller map widths, in that onboard storage and computation is minimized for the CM, and it is also likely that many more suitable map areas with the appropriate terrain statistics over the entire TERCOM map would be available for use in fixing.

For the baseline CMCA mission, the requirements for CMCA avionics can easily be met by state-of-the-art INSs, Doppler radars, and position-fixing radars. Consequently, technology issues are not the key issues in selecting the CMCA avionics suite; rather, the key issues are cost, nuclear hardness, and commonality with equipment already in the inventory.

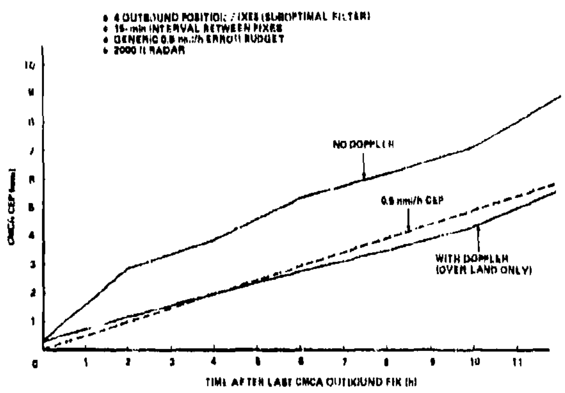

Figure 13. Impact of Doppler aiding on CMCA INS performance.

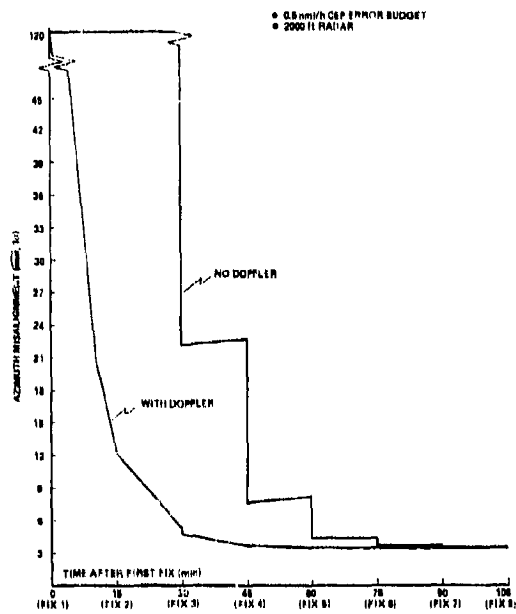

Figure 14. CMCA azimuth misalignment calibration.

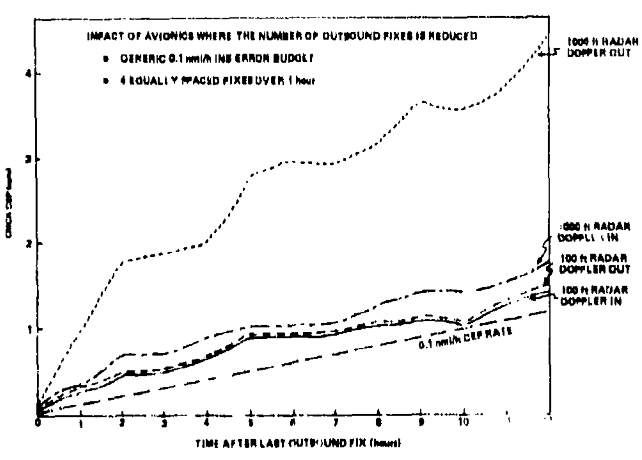

Figure 15. Impact on avionics when the number of outbound fixes is reduced.

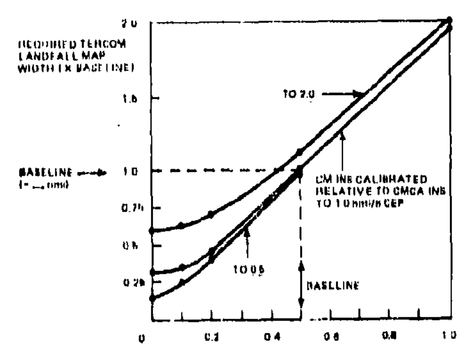

Figure 16. Required TERCOM landfall map widths versus CMCA INS quality.

4. TRANSFER ALIGNMENT/CALIBRATION ISSUES

Transfer alignment was addressed using a 10-state suboptimal position-matching filter. The states were two horizontal position errors, two horizontal velocity errors, three attitude errors, and three gyro drifts—all relative to an assumed-perfect CMCA INS. Some of the effects studied included different types of maneuvers and maneuver times within a 30-minute transfer-alignment period, longer alignment times, CM heading sensitivities, and in-air gyrocompassing.

Figure 17 shows the subsequent CEP error growth rate for three different types of maneuvers occurring in the transfer-alignment period of 30 minutes. It is apparent that for a 1-nmi/h relative calibration requirement and for the imposed constraints, a 45-degree-heading change maneuver is unacceptable for subsequent CM flight times longer than about an hour. However, Figure 18 shows that if the 45-degree-heading change occurs at the beginning of the alignment period, a near-acceptable error growth rate is achieved for slightly over 2 hours. Figure 19 shows the results for longer alignment times up to 60 minutes using a single S-turn. Here it is noted that as the alignment times are increased, the single S-turn results in significant improvement in the CEP.

Figure 20 shows the results for the case of a single S-turn in a 30-minute transfer-alignment period where the CM subsequently flies straight ahead after launch (trajectory B), and for the case where the CM makes a turn after launch and then flies straight ahead (trajectory A). The difference in the subsequent CEP error growth rate is due primarily to the sensitivity of the inertial-system error growth rate to the final trajectory heading. This is an effect commonly seen in long-term aircraft inertial-navigation problems and it is an important effect for long-range air-to-ground missiles.

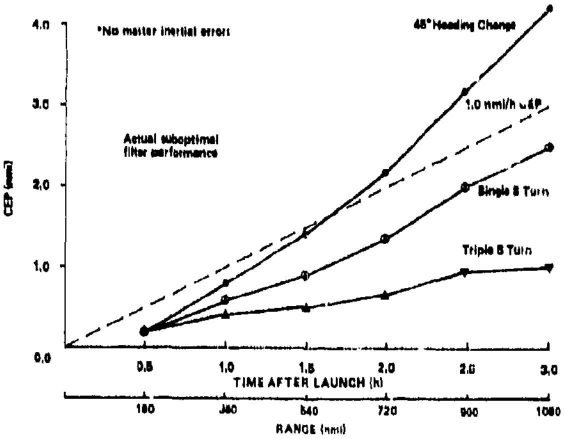

Figure 17. CM CEP versus time (range) after launch for a 45-deg heading change, single S-turn, and triple S-turn alignment maneuvers.

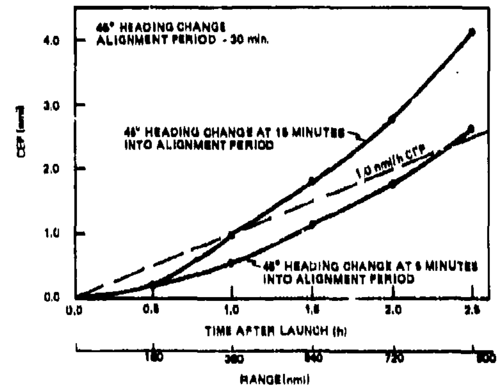

Figure 18. CM CEP versus time (range) launch for 45-deg heading change maneuvers executed at 15 and 5 minutes into a 30-minute alignment period.

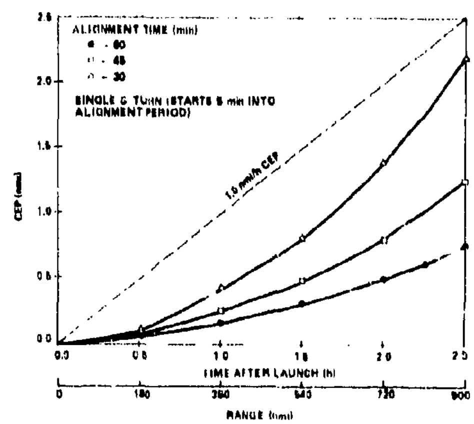

Figure 19. CM CEP versus time (range) for 60-, 45-, and 30-minute alignment periods.

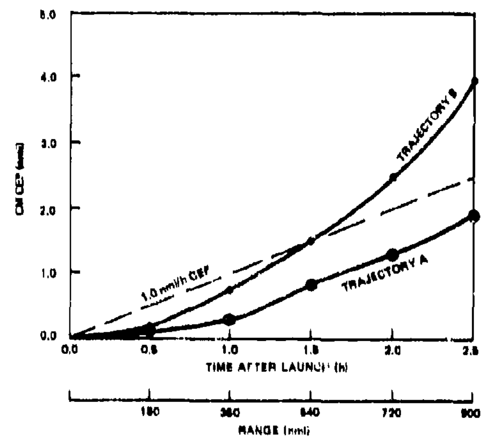

Figure 20. CEP versus time (range) after launch for CM trajectories A and B.

The use of either single-position or two-position in-air gyrocompassing for extended periods of time was also investigated. Possible benefits of in-air gyrocompassing are that better calibration of the CM guidance set may be achieved and that the potential exists for eliminating maneuver requirements. Figure 21 shows the results in terms of azimuth misalignment of the CM guidance set for the single-position and two-position in-air gyrocompassing cases, as well as for the S-turn transfer-alignment maneuver previously discussed. The azimuth error in the latter case is significantly less than the in-air gyrocompassing cases. Figure 22 shows the resultant CEPs for all three cases. The S-turn transfer-alignment maneuver is clearly superior to in-air gyrocompassing schemes.

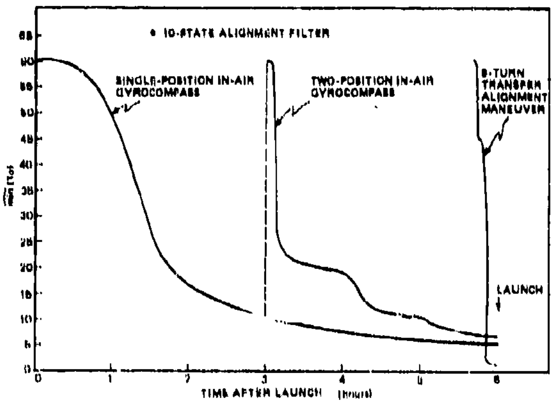

Figure 21. Azimuth misalignment calibration.

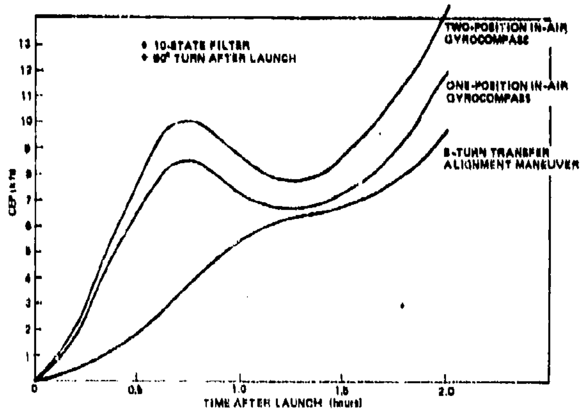

Figure 22. CM error only after launch for various in-air alignment schemes.

Figure 23 presents results for the gyro-drift estimation for the three in-air alignment schemes. Note that the gyrocompass cases always result in better estimation of the gyro-drift parameters. A logical combination of the approaches, then, would be to do in-air gyrocompassing for as long as possible during the overwater portion of the CMCA flight, and then to do a maneuver within a period of 30 minutes prior to launch to bring the azimuth error down to acceptable levels.

In summary, various options are available for use in transfer alignment and calibration of the CM guidance set. Many of these options appear to give acceptable CEP error growth rates according to the baseline error allocation. Which option is chosen would appear to be primarily a function of operational constraints such as the power and cooling requirements of the CM INS.

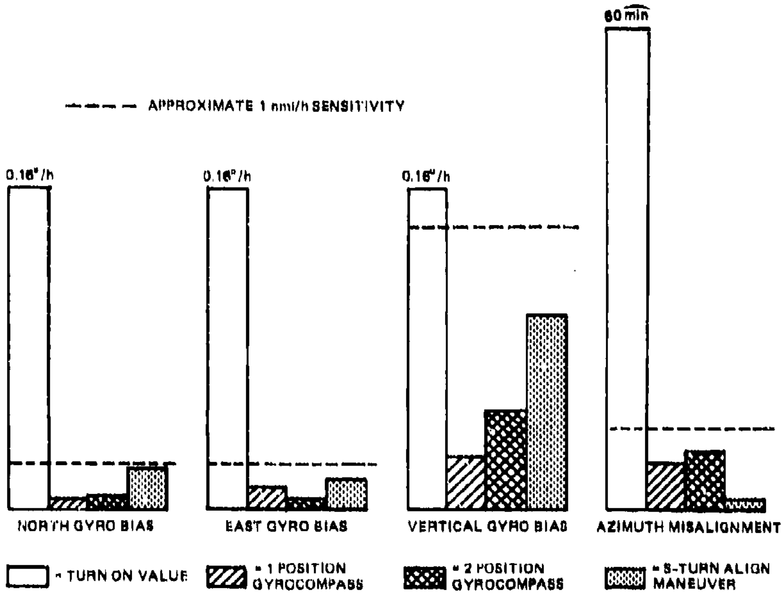

Figure 23. CM critical parameter estimation for various in-air alignment schemes.

5. BASELINE-MISSION EVALUATION

The previous sections have described the tradeoffs conducted for the CMCA avionics and for transfer alignment and calibration. The intent of this section is to present some overall system-level results, including both transfer-alignment and avionics errors.

The CM flight profile that was used in this study is shown in Figure 24. An S-turn transfer-alignment maneuver is used onboard the aircraft, and is followed by launch of the CM. The CM then descends to low level, makes a 90-degree turn and flies for a considerable distance until Fix #1; it subsequently makes five more fixes on its course into the target area. Each of the fixes updates the CM guidance system's knowledge of position, velocity, attitude errors, and gyro-drift errors. Consequently, the required TERCOM map widths decrease as a function of the number of fixes. The smaller map widths allow more accuracy at each fix, until at Fix #6 the accuracy at the fix is actually much better than the accuracy on target.

Figure 25 shows the nondimensional total CM crossrange error after launch for launches that occur at two different times after the last CMCA outbound fix. The dotted lines show the allowed 1-sigma crossrange error at each fix location. Note that the allowed error decreases because the map widths decrease. As can be seen from this figure, the error allocation has resulted both in acceptable errors at each fix time and in an acceptable on-target CEP. The final CEP is also a strong function of how far the cruise missile must fly from the last TERCOM map to the target.

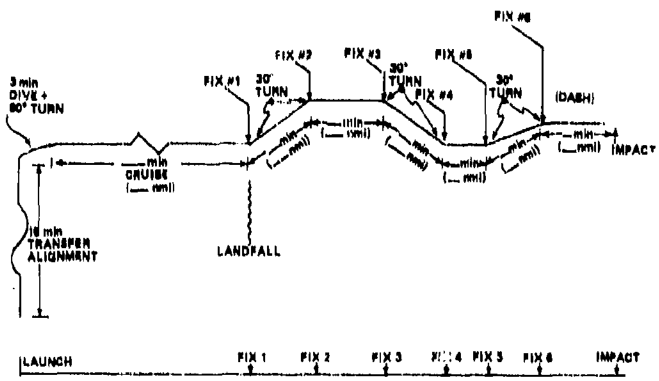

Figure 24. CM flight profile.

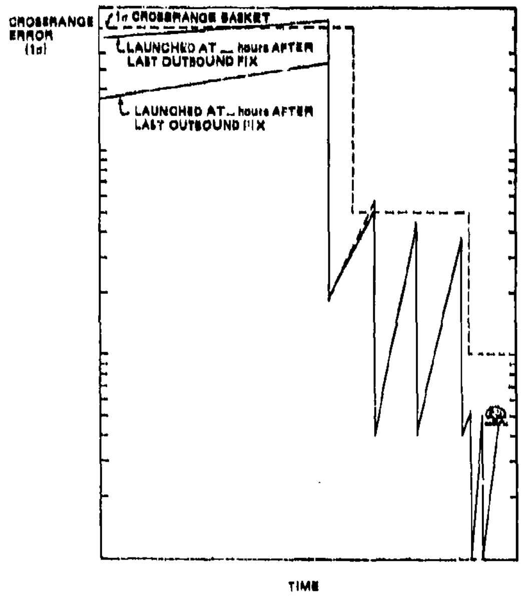

Figure 25. CM crossrange error after launch.

6. CONCLUDING REMARKS

A representative CMCA/CM weapon-system mission has been used to evaluate the system-level error allocation, and it has been shown that a CMCA navigation error rate of 0.5-nmi/h (CEP), or less, and a relative CM navigation error rate of 1-nmi/h (CEP), or less, results in an acceptable high probability of overflying the first landfall TERCOM map, as well as the maps enroute to the target. The key issues in implementing a CMCA navigation and guidance system do not appear to be performance issues since the requirements can be met by well-known state-of-the-art avionics elements.

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ACKNOWLEDGMENT

The work presented in this paper was performed by The Charles Stark Draper Laboratory, Inc. under Contract F33657-78-C-0473 with the Air Force Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio.[7] The Air Force program manager was Capt. W. Kraus (ASD/YYEM).

The authors acknowledge the assistance of other members of the Draper Laboratory study team. In particular, C. Wakefield and D. Lanza conducted many of the simulations reported herein.

Publication of this paper does not constitute approval by the U.S. Air Force of the findings or conclusions contained herein.

A FLIGHT SIMULATION INVESTIGATION ON THE FEASIBILITY OF CURVED APPROACHES UNDER MLS GUIDANCE

by

L.J.J. Erkelens
National Aerospace Laboratory NLR
Anthony Fokkerweg 2
1059 CM AMSTERDAM
The Netherlands

SUMMARY

This paper describes a simulation investigation concerning the possibilities of executing laterally curved approaches with a wide body type of aircraft in a MLS environment. The approach path variables were: final approach intercept altitude and angle of the turn. An earth fixed circular segment connected the straight preturn segment with the final segment. A flight director operating in the ILS tracking mode, supplied with minor modifications in the roll bar drive, has been used as the primary instrument for guidance. Additional provisions have been made to enable the pilot to monitor the approach. A total number of about 450 curved approaches, performed by three pilots, have been flown on the simulator under various weather conditions.

In addition to tracking data, subjective information like pilot ratings and comments were gathered. It turned out that curved approaches, with turn angles up to 180° can be carried out safely, provided that the altitude at which the turn is completed is not less than 305 m (1000 ft). Special provisions are needed with respect to the flight director roll bar drive, in order to achieve accurate tracking on the curved segment in strong wind conditions.

LIST OF SYMBOLS AND ACRONYMS

a_n	normal acceleration
ATD	along track distance: distance-to-go to the approach path intersection with runway centreline, measured along the nominal approach path projection on the horizontal plane
c.g.	centre of gravity
DME	Distance Measuring Equipment
F	turbulence intermittency factor
FAA	Federal Aviation Administration
HSI	Horizontal Situation Indicator
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
L	distance between approach path intersection with runway centreline and azimuth antenna site
mac	mean aerodynamic chord
MLS	Microwave Landing System
PR	pilot effort rating
PR_z	normalized pilot effort rating
r	radius of turn
TCP	turn completion point
TIP	turn initiation point
V	airspeed
VMC	Visual Meteorological Conditions
$W_{1,2,3}$	indication of the three considered weather conditions
x_a	x co-ordinate of aircraft position
x_o	horizontal distance between the approach path intersection with runway centreline and the turn completion point
$\bar{x}$	average value of a particular item to be rated
y_a	y co-ordinate of aircraft position
z_a	z co-ordinate of aircraft position
α	turn angle (positive for right-hand turns)
γ_o	nominal angle of descent of the approach path
ϵ	vertical angular path error, positive if aircraft above glide path
η	cross track deviation
θ	elevation angle of aircraft position with respect to the elevation antenna site; pitch attitude
ξ	vertical path deviation
ρ	slant range between DME transmitter and aircraft
σ	lateral angular path error, positive if aircraft right of track
σ_x	standard deviation of a particular item to be rated
τ	time constant
φ	roll angle
φ_o	roll angle bias
ψ	azimuth angle of the aircraft position with respect to the azimuth antenna site

1 INTRODUCTION

Due to the narrow coverage in both azimuth and elevation, the present-day Instrument Landing System (ILS) can only provide guidance along a straight line approach path.

When the Microwave Landing System (MLS) will be put into service on civil airports not only a means for more precise approach guidance becomes available, but moreover MLS yields the advantage of offering more flexibility in adapting the shape of the approach path profile to the local circumstances of a particular airport site.

Due to the wide coverage in both azimuth and elevation as illustrated in figure 1, MLS yields the possibility of offering guidance along curved or segmented approach paths.

From several investigations (e.g. Duning, K.E., 1973) it appears that curved approach paths, with simultaneous vertical and lateral curvatures, are less suitable for application in civil aviation.
Since IFALPA with respect to the FAA advanced notice of proposed rule making (ANPRM 74-12) rejected approach procedures below 1500 ft, which require rates of descent in excess of 1000 ft/min or multi descents paths, only lateral curvatures will be considered.

In the present investigation seven laterally segmented approach profiles have been selected with widely different values of the characteristic profile parameters in order to include a wide range of approach paths within coverage of the MLS.

The aim was to establish limits with respect to the turn angles and the final intercept altitudes for a slow-manoeuvering type of aircraft.

2 APPROACH PATH PROFILE GEOMETRY

2.1 General

The investigation was restricted to approach paths being composed of three segments: a straight preturn segment, a circular segment and a straight final segment, whereas the angle of descent is constant along the entire approach path.

A sketch of the basic geometry of the laterally segmented approach paths is presented in figure 2, as shown the projection of the curved segment on the horizontal plane has been chosen circular.

The approach path is characterized by:
- the length of the final segment (x_o)
- the turn angle (α)
- the turn radius of the curved segment (r)
- the angle of descent (γ_o)

To determine the aircraft's position relative to the nominal path the "along track distance" (ATD) has been introduced. The ATD is representing the distance-to-go, measured along the projected approach path on the horizontal plane, as illustrated in figure 2.

The position of the aircraft with respect to the approach path can be expressed in:
- along the track distance (ATD),
- cross track deviation (η), being the horizontal distance from the nominal path, and
- vertical path deviation (ξ), being the vertical distance from the nominal path.

A mathematical formulation of the approach path, including a derivation of the formulas for determining along track distance, cross track deviation and vertical path deviation is presented by Erkelens, L.J.J., (1978). In figure 3 the computations have been summarized in a flow diagram

2.2 Selection of the approach paths for simulation

In the simulation program a number of seven different approach paths were chosen. Fixed values with respect to turn radius and angle of descent have been established for all approach paths, being 2778 m (1.5 nm) for the turn radius and 3 degrees for the angle of descent. This turn radius requires, at a speed of 82.3 m/s (160 kts) a bank angle of approximately 14 degrees.

Furthermore the various horizontal approach path profiles have been defined by combining three turn angles (45°, 90° and 180°) with three lengths of the final segment. The length of the final approach segment has been chosen in such a way that the transition from the curved to the final segment takes place at altitudes of 122 m (400 ft), 305 m (1000 ft) and 457 (1500 ft) respectively. The 122 m height was selected because a curved approach, including a final intercept altitude of 122 m, might create a solution for the noise abatement problem of runway 19 R at Schiphol airport.

The length of the preturn segment has been established on 2.5 nm, corresponding to a distance covered during a flight of approximately one minute with a speed of 160 kts.

A summary of the characteristic parameters of the seven selected approach profiles is presented in table 1. Figure 4 shows the horizontal profiles, depicted in the map of the visual display model.

3 GUIDANCE PRESENTATION

3.1 General

In order to determine the aircraft position relative to the desired approach path, the following ground facilities must be available for an actual curved approach:
- a MLS elevation transmitter, yielding the elevation angle θ,
- a MLS azimuth transmitter, yielding the azimuth angle ψ
- a precision DME transmitter, yielding the slant range ρ.

Both elevation and azimuth transmitters supply conical θ and ψ planes according to the characteristics of an actual MLS. For each arbitrary approach path, being within the space determined by the MLS coverage limits, guidance can then be obtained.

The provided θ, ψ and ρ data will have to be transformed, by onboard computations, into aircraft position relative to the selected approach path. A derivation of the formulas for these computations is presented by Erkelens, L.J.J., (1978).

The simulated MLS azimuth and elevation sites are assumed to be located on the normal ILS localizer and glide path antenna sites. The DME is assumed to coincide with the azimuth transmitter. In the present investigation the azimuth transmitter has been positioned on the extended centreline at a distance of 305 m (1000 ft) behind the runway end, whereas the elevation antenna has been located 305 m (1000 ft) behind the runway threshold and at a lateral distance of 120 m (394 ft) from the centreline. The simulated runway length amounts to 3353 m (11000 ft).

3.2 Scaling of cross track and vertical path deviations

Along the segmented approach path the cross track and vertical path deviations, η and ξ respectively, can be scaled to angular errors, corresponding with glide slope and localizer errors in the ILS case.

The requirements for ILS localizer and glide slope sensitivities are provided by ICAO (1968). Application of these requirements on the afore-mentioned runway length, azimuth antenna location and the specified approach path angle of descent leads to the following sensitivities:
- an angular localizer deviation of ± 1.68 degree for a 2-dots localizer needle deflection, corresponding to the maximum localizer current of 150 μ A.

- an angular glide slope deviation of $\pm$ 0.72 degree for a 2-dots glide slope needle displacement, corresponding to the maximum glide path current of 150μA.

This angular proportionality will provide an increasing sensitivity as the aircraft approaches the touchdown point, which is in agreement with the usual ILS guidance practice.

However, when the aircraft is very far from touchdown it would not be rational to maintain a sensitivity which alters with distance. Therefore the angular error scaling has been applied only from a certain ATD down to touchdown. When the aircraft is further away than this particular ATD, the scaling will be related to fixed cross track and vertical path distances. For both lateral and vertical path errors different ATD's have been established.

The maximum values for the off-track distances in this simulation investigation, have been established on 400 m for the cross track deviation and 150 m for the vertical path deviation. The scaling has been depicted in figure 5.

3.3 Flight director

The flight director was programmed on an EAI 680 analog computer. The ILS tracking mode of the DC-10 flight director has been used for the basic flight director model. Block diagrams of the pitch and roll bar drive are presented in figures 6 and 7 respectively.
The following modifications, compared to the original ILS tracking mode, were applied:
<u>pitch bar channel (Fig. 6)</u>:
During the turn the versine function, normally used in the localizer intercept mode was switched on, supplying elevator commands to compensate for bank angle during curved segment tracking.
<u>roll bar channel (Fig. 7)</u>:
When the aircraft is proceeding along the curved segment, tracking has to be performed about a biased roll angle attitude. The roll angle bias is dependent on the aircraft velocity and turn radius. In the present simulation the roll angle bias φ_o was determined originating from a fixed nominal airspeed of 160 kts and a turn radius of 1.5 nm, yielding φ_o = 14 degrees. During the turn this additional φ_o signal was summed via a low-pass filter with the localizer error signal.

Transition from a straight to a circular path and reverse would require an instantaneous change in roll angle. In case of an actual aircraft, the entry of a turn will take some time. So in order to deliver the aircraft on the desired circular path with a roll angle, required for the particular turn radius and speed, the roll command has to be initiated some distance before reaching the end of the preturn segment. For the same reason the exit from the turn has to start before the final segment is reached. The distance covered during entering or terminating a steady turn was determined; for the present simulation a distance of approximately 185 m (0.1 nm) has been applied.

Initially only the two above-mentioned provisions had been applied to the existing roll bar drive.

During low cloud base approaches the pilots complained that the flight director did not bring them on the desired final approach track after passing the turn completion point. It turned out that in the existing roll attitude loop (see Fig. 7) a washout filter with a time constant of 60 seconds caused this trouble. After the φ_o signal is switched off the roll bar signal will contain, due to this large time constant, a remnant roll signal for a considerable time. The problem was solved by reducing the time constant to 15 seconds and be resetting the lagged roll filter (τ = 30 s) and the washout filter (τ = 15 s) after the φ_o signal has been terminated by the turn switch.

After this modification had been applied no further remarks about this item were made by the pilots. The discussed modifications are indicated by dashed lines in figures 6 and 7.

3.4 Horizontal situation indicator

The horizontal situation indicator (HSI) could operate in two different modes:
- "normal ILS mode". In this case the position of the aircraft relative to the extended centreline of the runway is displayed,
- "MLS mode". In this mode the instrument indicates the position of the aircraft relative to the desired track of the particular approach path.

In the left DME window of the HSI the along track distance was displayed in both the normal ILS and the MLS mode.

3.5 Pictoral display

A Tektronix 432 oscilloscope (screen dimensions 10 x 8 cm) was used to display the horizontal and vertical profile of the selected curved approach path. Moreover the picture was supplemented with the momentary position of the aircraft. The image on the CRT was generated by the analog computer.

4 SIMULATED TYPE OF AIRCRAFT

Since an aircraft with high mass and inertia properties may be expected to be critical with respect to the curved approach capability, a wide-body type of aircraft was used in the simulation, having the characteristics of a B-747 aircraft.

The approach condition with gear down and flaps fully deflected was simulated. The simulated aircraft mass and c.g. position were chosen 265000 kg (maximum landing weight) and 25 % mac (mid c.g. position) respectively. In that case the reference speed is 73.0 m/s (142 kts); taking into account a correction for the considered wind conditions, the final approach speed becomes 82.3 m/s (160 kts).

This simulated aircraft was provided with a yaw damper and an autothrottle.

Time histories of responses of the simulated aircraft have been compared with time responses of the actual B-747 aircraft derived from Hanke, R.C. (1970).

A good agreement appeared to exist with respect to the dynamics of the simulated and the actual aircraft, both symmetric and asymmetric; also a comparison between the dynamic characteristics of the simulated and the actual aircraft was carried out by an evaluation pilot. He considered the characteristics and control forces in good agreement with those of the actual aircraft.

5 TEST FACILITY

5.1 NLR moving-base flight simulator

The NLR has at its disposal a versatile moving-base flight simulator especially designed for research purposes. Sophisticated systems and components have been used to achieve a simulation of real flight as realistic as possible in all the considered aspects.

The single-seat cockpit of the flight simulator was mounted on the four-degrees-of-freedom motion system (see Fig. 8).

The installed Singer/Link-Miles Mark V Visual System comprises a rigid three-dimensional model, scaled at 2000 : 1, to represent an aera of 13.2 x 5.2 nautical miles including an airfield with Category II lighting and a surrounding terrain. The model is viewed through a closed-circuit colour television system.

Visibility effects such as clouds, haze and fog are introduced by electronically altering the terrain image. The visual scene appearing on the monitor is collimated to provide infinity images throughout the range of normal head movement.

5.2 Cockpit instrumentation

A picture of the instrument panel including the simulated outside view is presented in figure 9. As can be seen the normal instrument panel is supplemented by a pictorial display, described in section 3.5.

Two additional instruments have been installed indicating the aircrafts azimuth and elevation angles relative to the MLS sites.

6 DESCRIPTION OF THE TEST PROGRAM

6.1 Approach procedure

Each approach was started with the aircraft in the final approach configuration which implied that no configuration changes (gear, flaps) had to be applied by the pilot while performing the approach.

Before each simulated approach was initiated the aircraft was released from an initial condition, which can be described as follows:
- aircraft trimmed for an airspeed of 82.3 m/s (160 kts) (V_{ref} + 20 kts) and the correct rate of descent for a 3 degrees glide path. Heading corrected for the prevailing wind,
- aircraft position: at the beginning of the preturn segment. An initial off-track deviation has been applied of ½ dot on the deviation indicators right and above the nominal approach path.

The pilot initiated the start of the approach by pushing the "operate" button. One second before the roll command on the flight director for turn entry was activated a turn annunciator on the instrument panel was alluminated, warning the pliot that the roll command for the turn was about to arrive. One second before the roll command for the turn exit was activated the annunciator was switched off.

During the final approach segment no marker (e.g. middle marker) signals were simulated.

The pilots did use the flight director as the primary instrument for approach guidance. However, also a horizontal situation indicator was available, which could operate in the normal ILS mode or in the modified (MLS) mode (see section 3.4), the selection between these modes was within pilots discretion.

For monitor purposes the pictorial display and azimuth and elevation indicators were available. By means of approach charts the pilots were informed about the altitude, along track distance, azimuth and elevation angle at the check points TIP and TCP.

6.2 Meteorological conditions

The practicability of the seven selected approach profiles has been investigated under three different meteorological conditions w_1, w_2 and w_3, which are specified in figure 10.

As appears two numbers have been used for indicating the cloud base. This is due to the fact that for cloud break simulation a transition range of 30 m (100 ft) is used in the visual system in order to account for a realistic presentation of the cloud break phenomenon.

The wind shear profile did contain shear gradients of 0.17 $\frac{m/s}{m}$ (10 kts per 100 ft), whereas a fixed wind direction was assumed. The present wind shear is based on the ICAO estimation that wind shears in excess of 10 kts per 100 ft may be expected on 4 per 1000 approaches and take-offs. It has to be emphasized that the applied shear gradient is much stronger than the wind shear of .07 $\frac{m/s}{m}$ (4 kts per 100 ft) considered in FAA Advisory Circular 120-29 (1970), with respect to flight director and autopilot approval conditions. Since the runway heading was 240°, on final a left crosswind of 7.7 m/s (15 kts) existed for condition w_1 and w_2 (altitude > 60 m). Under condition w_3 (altitude > 30 m) a right

crosswind of 2.6 m/s (5 kts) was experienced.

The atmospheric turbulence generated during the simulation was based on the model of Jansen, C.J. (1977). This model is capable of generating time histories which reproduce the quality of "intermittency". The non-Gaussian distribution of velocity differences in real atmospheric turbulence is connected to this quality. The intermittency can be controlled by a single parameter F, and was selected in this simulation to a moderate value (F = 0.2).

6.3 Experimental design

The total experiment was divided into two programs. During the first program only two weather conditions were considered (w_1 and w_2). The first sessions for each pilot did concern ILS approaches so as to become familiarized with the flight simulator. During the remaining sessions various MLS approach paths were executed for condition w_1 and w_2 in a pseudo-random sequence.

In the additional program only weather condition w_3 was considered. No ILS sessions were performed and the sessions for the various MLS approach paths were also presented randomly to the pilots. Finally, it has to be remarked that under weather conditions w_1 and w_2 the autothrottle was operating, whereas under condition w_3 the throttle was controlled manually.

Each session was divided into a familiarization part and a test part. It was composed as follows:
- 1 familiarization ILS approach
- 2 familiarization MLS approaches of the approach profile concerned
- 5 test MLS approaches of the same profile.

The weather condition was kept constant during one session. The pilot was only informed about the cloud base, runway visual range and surface wind. The impression was given to the pilots that wind shear could occur randomly over the runs of one session, although the same wind shear model was maintained during a session.

After each test run the pilot was asked to fill up a pilot rating card. After the session had been completed a debriefing followed, during which the pilot was asked to fill up a questionnaire and to give oral comments on several items, which were tape-recorded. Moreover he was allowed to give free comments.

Besides these subjective results also objective data were obtained. During two points on the approach a number of parameters were recorded concerning the position of the aircraft relative to the nominal approach path and its vertical and horizontal speed. The data were recorded at the following moments:
1) when passing the turn completion point TCP, that is when the along track distance (ATD) of the aircraft is equeal to the ATD of the TCP,
2) when passing the "100 ft window", that is when the along track distance of the aircraft is equal to 582 m (0.314 nm), corresponding to a nominal approach path altitude of 30 m (100 ft).

Since 3 pilots were participating in the simulation experiment, and three weather conditions had been considered a total of 63 MLS sessions were performed.

6.4 Pilots

During the test phase the simulated aircraft including the instrumentation was evaluated by a B-747 co-pilot of the KLM (Royal Dutch Airlines). This pilot did not participate in the further investigation.

Two other KLM pilots, a B-747 co-pilot and a DC-10 co-pilot respectively and an engineering pilot of the RLD (Department of Civil Aviation of the Netherlands), involved in airworthiness flight testing and with DC-10 airline experience, participated in the simulation experiment.

7 TEST RESULTS

7.1 Objective data

As mentioned in section 6.3 at two points of the approach path, data with respect to aircraft state and relative position to the nominal approach path have been recorded. These points are:
- the 100 ft point,
- the turn completion point (TCP).

Measured data, concerning the localizer and glide slope deviations for the simulated approaches at these datum points have been summarized in histograms.

For the purpose of airborne system evaluation by the FAA (1970) a definition is given for a successful approach. Concerning glide slope and localizer deviations, according to this reference, a successful approach is one in which at the 100 ft point:
- the deviation from the glide slope does not exceed ± 75 μA corresponding to ± 1 dot on the ILS indicator,
- the airplane is positioned so that the cockpit is within, and tracking so as to remain within, the lateral confines of the runway extended.

  So far as the present investigation is concerned, the maximum acceptable deviation becomes ± 25 μA corresponding to ± $\frac{1}{3}$ dot.

The above mentioned deviations of 75 μA and 25 μA yield the "100 ft window", as indicated in figure 10. With respect to the path deviations at the turn completion point (TCP) a window has been indicated in figure 11 based on a deviation of ± 35 μA (± 0.47 dot) on the indicators for both glide slope and localizer error. The value of ± 35 μA has also been derived from FAA (1970) and is related to the performance for category II flight director approval.

The dimensions of both the 100 ft and the TCP window are presented in the table of figure 11.

Since the participating pilots after all did consider profiles 1 and 2 (TCP at 122 m (400 ft)) unacceptable with a view to standard airline operation routines, separate histograms were presented for approach profiles having their TCP at 122 m (profiles 1 and 2) and profiles having the TCP at 305 m or above (profiles 3 through 7).

Because of lack of data for the ILS approaches under weather condition w_3, in figures 12 and 13 only histograms for w_1 and w_2 are presented for the ILS case.

Comparing the histograms of localizer deviation at the 100 ft point for ILS and MLS approaches (condition w_1 and w_2 only) it can be concluded that the distributions for profiles 3 through 7 and for the ILS approaches are quite similar, whereas for profiles 1 and 2 the histograms show greater deviations (see Fig. 12). It appears that the tracking errors for the w_3 condition are much greater than those for the w_1 and w_2 conditions.

So far as the glide slope deviation is concerned (Fig. 13) it appears that no significant differences exist between the histograms for the MLS approaches and the histograms for the ILS approaches, concerning the w_1 and w_2 conditions.

For the conditions w_1 and w_2, where no shear effects are present at the moment of observation, the aircraft is generally above the nominal glide path. Moreover many data are exceeding the + 75 μA (1 dot) limit.

The distribution of data points for profiles 1 and 2 in the w_3 condition differs considerably from that of the profile series 3 through 7.
As is clearly illustrated by a mutual comparison of the glide slope deviations of conditions 1 and 3 (no wind shear effects at the moment of observation) and the condition 2 (shear effect present), the mean value of the distributions for conditions without wind shear indicates an "above glide path" position, whereas in the wind shear case a mean "below glide path" results.

Histograms of the data at the completion point (TCP), classified to the height of the TCP (122, 305 or 457 m), are presented in figures 14 and 15 for localizer and glide slope deviations respectively. As appears from figure 14 almost all data points are situated on the left side of the localizer, indicating that the aircraft ended the turn always on the inner side of the turn which is due to the fact that during the turn a constant roll angle signal φ_0 was added to the roll bar drive, leading to a turn radius of:

$$r = \frac{V^2_{ground}}{g \tan \varphi_0} .$$

This yields the correct ground track in a no-wind condition. If wind is present, however, for an approach profile having a 180 degrees turn, the aircraft initially meets a tailwind on the circular segment which gradually changes into a headwind on the final part of this segment. The resulting variable ground speed will move the aricraft initially to the outerside of the circular segment, due to the increasing turn radius. After the tailwind has been altered into a headwind the aircraft will move to the innerside of the segment , due to the reducing turn radius.
The tracking errors resulting from the above mentioned deviations will generate additional roll angle signals for the roll bar drive.

The effect is presented in figure 16 showing the actual aircraft tracks relative to the nominal track of approach profile 7 for the three wind conditions considered.

The presence of headwind on the last part of the circular segment explains the concentration of data points on the left side of the localizer at TCP.

This unwanted behaviour of the simulated flight director, which can be solved by exchanging the constant roll angle command, as applied in the present simulation, for a variable - ground speed dependent - roll angle command, is also clearly illustrated if the localizer deviation histograms for condition w_2 are compared with the pilots for w_1 and w_3. The wind during the greater part of the turn was 10 kts in the w_2 condition and 30 kts in the w_1 and w_3 condition. In the w_2 case the localizer deviations are substantially smaller for all considered profiles.

The effect of wind shear on the glide path tracking accuracy at TCP can be observed if the glide slope deviation plots for w_2 and w_3 are compared (Fig. 15). The wind shear of condition w_2 (increasing headwind) is responsible for the fact that the aircraft is generally above the glide path at TCP, whereas the shear of condition w_3 (decreasing headwind) yields glide slope deviations at TCP in the opposite direction.

As can be seen from the glide slope deviation at TCP for approach paths 3 through 7 the data points are almost all within the 35 μA range, whereas a substantial part of the points for approach paths 1 and 2 are outside the 35 μA range.

7.2 Subjective data

7.2.1 Pilot effort ratings

After each test run was completed the pilot filled up an effort rating card to indicate the amount of effort he had to spend on the following items:
- horizontal path tracking
- vertical path tracking
- airspeed control
- total approach execution

The individual ratings have been normalized so as to enable a comparison between the ratings of the three individual pilots.

The normalization has been carried out according to the formula:

$$PR_z = \frac{PR - \bar{X}}{\sigma_x}$$

In figures 17 the normalized effort ratings for the total approach execution are presented. As appears no obvious relation can be obtained between the magnitude of effort rating and the type of approach profile. The relative high effort ratings for the ILS approaches may be due to the effect of learning, because all these approaches were carried out at the beginning of the test program. On the contrary, the various curved MLS approaches have been executed by each pilot in a random sequence.

If only the curved approaches are considered a slight trend of increased effort can be perceived for the profiles 1 and 2 (TCP at 400 ft), in particular this is true for the effort ratings for the total approach in the w_3 condition.

7.2.2 Pilot questionnaire

A total number of 63 questionnaires have been filled up by the three participating pilots. In order to provide a surveyable presentation of the responses to the various questions, including the relevant oral comments, the results will be considered separately for the approach profiles finally considered "acceptable" (profiles 3 through 7) and "unacceptable" (profiles 1 and 2).
The score of the responses for each of the 9 questions has been expressed in percentage of the total number of responses for the two series of approach profiles. The results are presented in the diagrams of figure 18.
Each question will be discussed hereafter.

Question 1

Preturn segment

Did you have enough time to get stabilized on this approach segment?

In all cases for both acceptable and unacceptable profiles the response to this question has been "yes".

It has to be remarked that in this simulation experiment the length of the preturn segment was fixed at 4630 m (2.5 nm) and the aircraft was initially positioned ½ dot above and right of the nominal path.

Question 2

Curved segment

Was the magnitude of the bank angle required for tracking the curved segment: acceptable, marginal acceptable, too large?

The answers marginal acceptable, marginal acceptable/too large and too large mainly came from pilot II, who stated that in the full flap approach condition the bank angle is normally restricted to about 15 degrees. The turn in the curved approaches with an applied radius of 2778 m (1.5 nm) requires a bank angle of 14 degrees at a nominal speed of 82.3 m/s (160 kts). However, due to effects of tailwind and/or of pilot response on tracking errors the actual bank angle may become much larger.

Question 3

Final segment

Did you have enough time to get stabilized on this approach segment?

The response score in figure 18 explains why the pilots did reject the approach path profiles 1 and 2.

In the next question the pilots did express the amount of effort spend during final segment tracking.

Question 4

Compared with the ILS approach, was the effort you did spend on performing the last part of the final approach:

Apparently more   About the same   Even less

The result, shown in figure 18, indicates that a significant higher effort is required for tracking the final segments of profiles 1 and 2 than for tracking the final segments of the remaining profiles. This was also shown in the analysis of the effort ratings given by the pilots for the total approach execution (see Fig. 17).

Question 5:

Total approach

Was this approach acceptable, with a view to standard airline operation routines?

The answers to this question were given as follows:
Concerning profiles 3 through 7:
76 % yes, with the remark that an improved flight director has to be available. After the flight director roll bar improvement, discussed in section 3.3 had been applied, no more complaints about the flight director roll drive were given.
24 % yes, so far as the particular MLS approach procedure is concerned;
no, with respect to the magnitude of the bank angle during curved segment tracking. This response came from pilot II only, the large bank angle remark has also been put forward under question 2.
Concerning profiles 1 and 2 the result was unanimously: no. The comments given on this item can be summarized as:
- a final intercept altitude of 122 m (400 ft) is too low, because too short time for stabilization on final is available.
  In particular, if at the final segment entry the aircraft has a considerable deviation from the nominal

track it is almost impossible to get the aircraft stabilized before reaching the decision height. Many of these simulated approaches would have lead, during actual approaches, to missed approaches.

Question 6

What is your opinion about this combination of intercept angle/ approach intercept altitude?

- No objections to this combination
- Intercept angle too large; altitude correct
- Intercept altitude too low; angle correct
- Combination of both angle and altitude yields problems

For the profiles 3 through 7 the pilots answered in all cases that they did not have objections to the presented combination of intercept angle and intercept altitude. However, in case of profile 1 and 2 they all were of opinion that the intercept altitude of 122 m (400 ft) was too low for both 45° and 90° intercept angles (Fig. 18). The pilots shared the opinion that with respect to stabilization the minimum safe altitude on final shall be approximately 305 m (1000 ft).

Question 7

Instrumentation

What do you think about the pictorial display?

- Very helpful
- I used it occasionally
- I did not use it very much

For all considered MLS approaches the pilots did not use the pictorial display frequently, as appeared from the answers given to this question.
The following percentages of answers were yielded:
For profiles 3 through 7:
87 % I did not use it very much
13 % I used it occasionally
For the profiles 1 and 2 these percentages were 94 % and 6 % respectively.

Question 8

During which segment(s) was the pictorial display an essential support to your task performance?

The answer to this question was in nearly all cases: none.
The reasons for making no use of this item were:
- The approach profile geometry was rather simple so that the need for a monitor display was absent.
- The location of the pictorial display on the instrument panel was such that the instrument was outside the scanning range of the pilot (see picture of Fig. 9).

However, the pilots did agree that if in case of a two pilots operation the pilot-not-flying would be able to monitor the approach on this pictorial display up to the final intercept, this instrument could be of any support.

Another application would be met during the approach path interception. However, this would require a modified lay-out of the presented image.

Question 9

Do you consider the approach equally well acceptable for airline operations with only the aid of the flight director and the basic flight instruments?

The result for profiles 3 through 7 was:
64 % yes, provided that the modified flight director is available
36 % of the answers was no. It appeared that additional position information was desired. The pilot comments on this question mainly contained the need for:
- a modified horizontal situation indicator, providing aircraft position relative to the nominal track,
- along track distance information,
- a turn annunciator.

The monitor display and the azimuth and elevation indicators were not considered to be necessary.
It will be evident that for the profiles 1 and 2 the answer on question 9 was unanimously no.

7.2.3 Summary of pilot remarks

Summarizing the oral comments provided by the three pilots during the test program and afterwards, the following notes can be made:

Approach path acceptance

- The approach profiles 1 and 2 (TCP at 122 m altitude) have to be considered "unacceptable" with respect to standard operation routines. The most important objection to the procedures is that there is not enough time to stabilize on the final segment. However, if a suitable flight director is available these approaches can be executed safely after some practice by the more experienced pilot.

  The opinion of the pilots was that possibly MLS approaches of the profile types 1 and 2 may be used as an additional support to existing curved approaches which are now to be performed merely visually. As an example the Canarsie approach on Kennedy airport was mentioned. In this particular case the glide path guidance could provide a guarantee that the correct altitude along the approach is maintained.
  Due to the high effort the pilot has to spend on tracking this very short final segment, the approach is considered to be not applicable for merely noise abatement purposes.

- The remaining approach profiles unanimously have been considered "acceptable". The general opinion existed that the magnitude of the interception angle was unimportant; the only decisive parameter was the altitude at TCP. Hardly any practice is required to perform these approaches.

One pilot did consider the bank angles occuring during the turn too large, while another did only complain incidentally about this item.

The use of autothrottles is of essential importance for the execution of curved approaches, thus enabling the pilot to pay full attention to the horizontal en vertical tracking tasks.

Flight director

- All three pilots did comment that the pitch bar was too slow.
- Initially the flight director did not bring the aircraft directly on the final approach segment. After the additional adjustments were carried out, this trouble disappeared.
- The lack of wind compensation, during the curved segment, in the roll bar drive was experienced by the pilots as inconvenient, however, they did accept this difficulty so long as there was sufficient time to become stabilized on the final segment.

Additional guidance information

The HSI operating in either the "normal ILS mode" or the "MLS mode" was used by all pilots. There was a slight preference for operation in the MLS mode. This was based on the fact that in that mode the instrument provides "all the way" position information. In the ILS mode operation the pilot is able to carry out an usual final approach intercept, which was considered by one pilot to be very advantageous, possibly influenced by the initial flight director roll channel problems.

The pictorial display was unanimously considered to be of minor importance to the approach guidance support, moreover, the azimuth and elevation indicators were considered to be superfluous. On the contrary the turn annunciator was experienced as a very useful feature.

8 CONCLUDING REMARKS

In the present simulator investigation the utility of a number of seven laterally curved approaches with various turn angles and final intercept altitudes, executed with a simulated wide body aircraft, has been investigated, assuming that guidance was provided by a Microwave Landing System (MLS). Three weather conditions have been considered which included moderate turbulence and strong wind shears, while 30.5 m (100 ft) was the minimum cloud base used in the experiment.

A flight director operating in the ILS tracking mode, supplied with minor modifications in the roll bar drive, has been used as primary guidance instrument. Additional provisions have been made to enable the pilot to monitor the approach. These concerned:

- a modified HSI, presenting aircraft position and heading information relative to the curved approach path,
- a turn annunciator, warning the pilot that the aircraft is about to enter or to leave the curved segment,
- a pictorial display, depicting on an oscilloscope the horizontal and the vertical profiles of the approach path, which has to be flown and moreover displaying the momentary aircraft position,
- an azimuth and elevation indicator, presenting the aircraft's azimuth and elevation angles with respect to the simulated MLS transmitters.

Originating from the approach path geometry and guidance presentation, as applied in this investigation, the general conclusion is that the acceptability of a particular approach path only depends on the altitude of the turn completion point (TCP). The angle of turn is not a decisive parameter.

Laterally curved approaches have to be regarded as impracticable under IMC with respect to standard airline operation implementation, if the turn completion point altitude is much less than 305 m (1000 ft).

Provided that the TCP altitude is at least 305 m (1000 ft) the average airline pilot will hardly need any practice, according to the participating pilots, to perform these approaches.

Although for IMC operations the pilots disapproved the approach paths with turn completion point (TCP) altitudes of less than 305 m (1000 ft), paths with substantially lower TCP altitudes flown in VMC under MLS guidance are estimated to be very useful to support existing curved approaches, now being carried out completely visually. As an example the Canarsie approach on Kennedy airport was mentioned.

Depending on the type of autopilot and flight director, provisions have to be made with respect to the roll channel in order to avoid large deviations during curved segment tracking. If a ground-fixed track has to be followed, the roll angle bias signal for roll control and roll bar drive has to be made dependent on the ground speed.

The modified horizontal situation indicator (HSI), providing the aircraft position relative to the nominal track, appears to be a useful instrument for monitoring. Also the presented along track distance, displayed in the DME counter was very much appreciated, as was the presence of the turn annunciator.

If the above mentioned monitoring aids are available there is no need for an additional pictorial display, so far as the tracking of this very simple type of approach is concerned. However, in case of more complex approach paths and moreover during the interception phase of the present curved approach paths a pictorial display system will be very useful.

Further investigation is required in order to decide whether the approach profiles qualified "acceptable" in the present investigation are still practicable if the interception of the MLS path and the configuration changes (flaps, landing gear) are taken into account.

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TABLE 1

Dimensions of the selected approach path profiles

approach profile number	altitude at turn completion point m (ft)	final segment length km (nm)	turn angle deg	altitude at turn initiation m (ft)	ATD at turn initiation km (nm)
1	122(400)	2.3 (1.3)	45	236(775)	4.5 (2.4)
2			90	350(1150)	6.7 (3.6)
3	305(1000)	5.8 (3.1)	45	419(1375)	8.0 (4.3)
4			90	533(1750)	10.2 (5.5)
5			180	762(2500)	14.5 (7.9)
6	457(1500)	8.7 (4.7)	90	686(2250)	13.1 (7.1)
7			180	915(3000)	17.5 (9.4)

<u>angle of descent</u> γ_o for all profiles 3^o, constant along the path

<u>turn radius</u> r for all profiles 2778 m (1.5 nm)

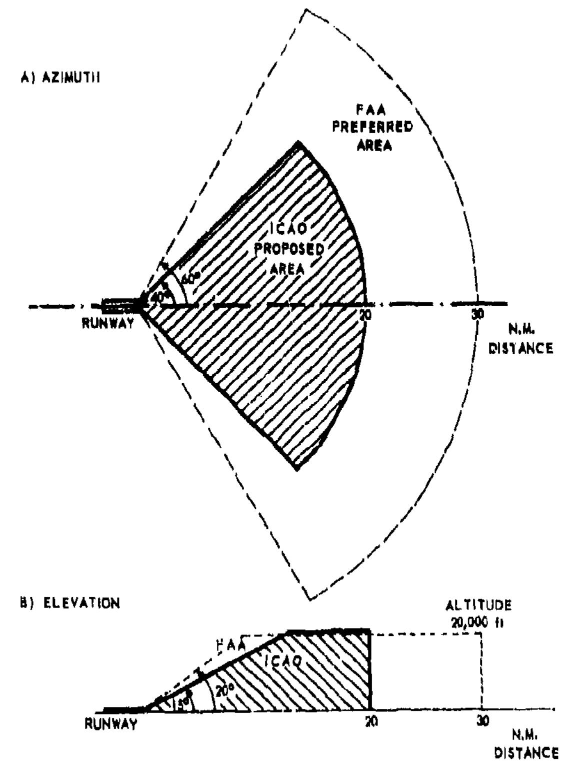


Fig. 1 MLS coverage area

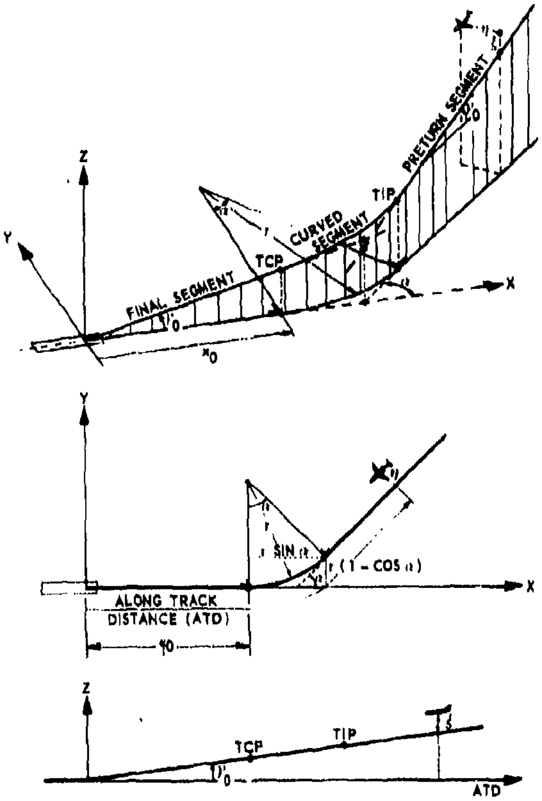


Fig. 2 Lay-out of the laterally segmented approach path

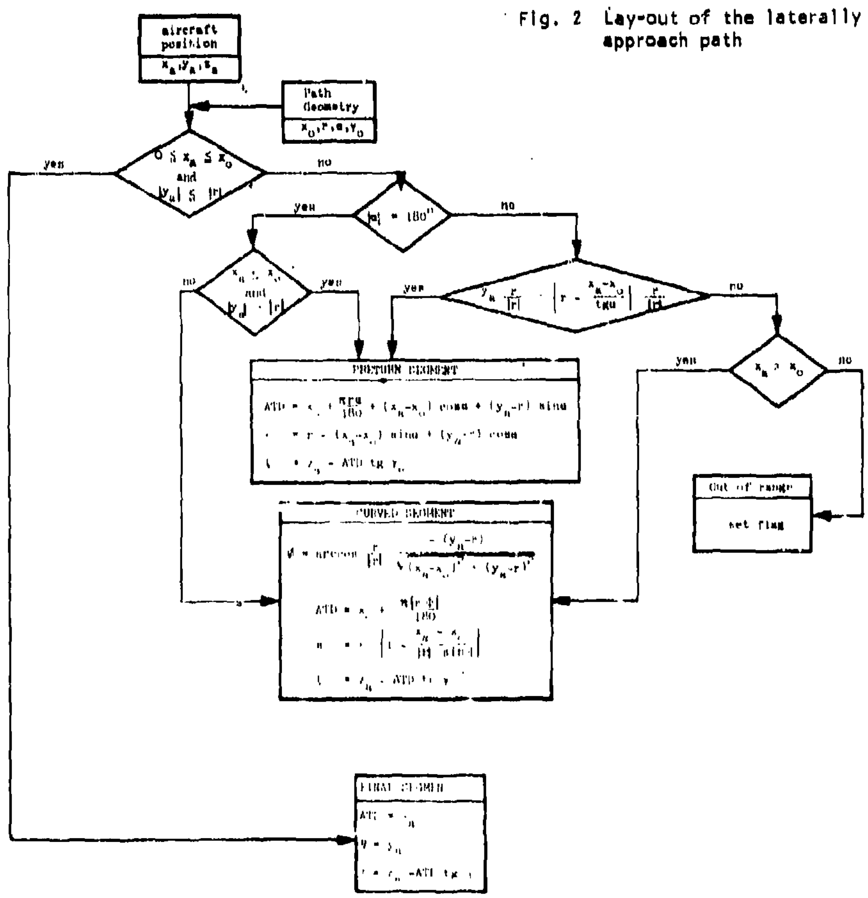


Fig. 3 Flow diagram for determining the aircraft deviations from the nom'nal approach path

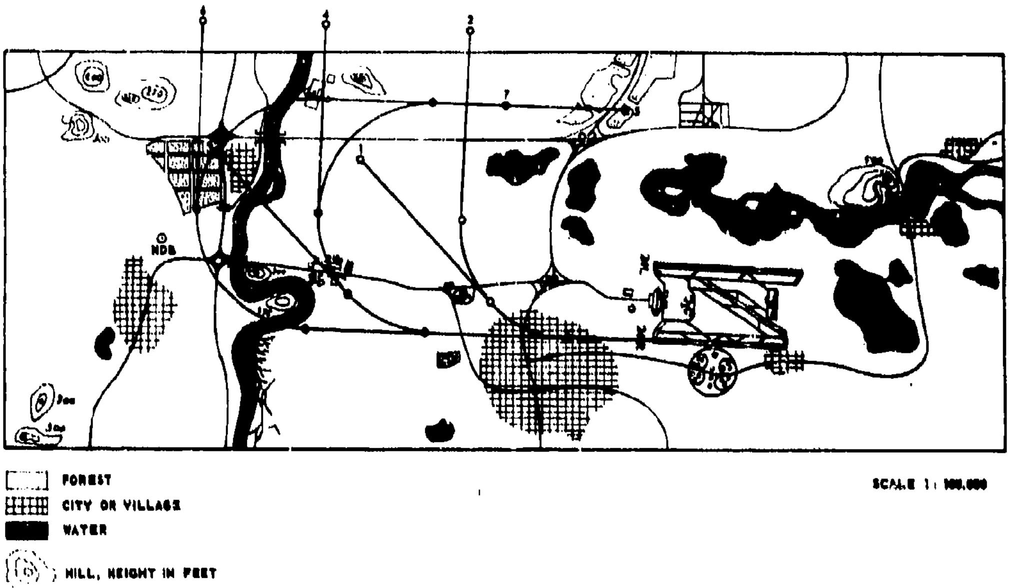


Fig. 4 Survey of the tracks of the seven approach paths, depicted in the map of the visual display model

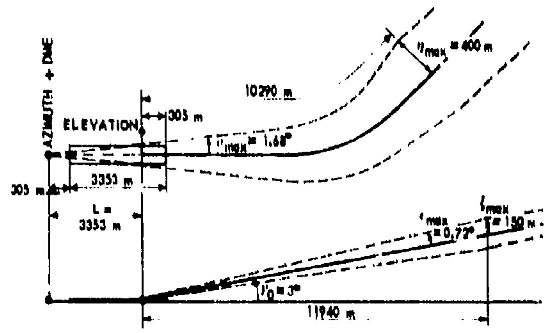


Fig. 5 Scaling of lateral and vertical path errors in case of the MLS lateral segmented approach path

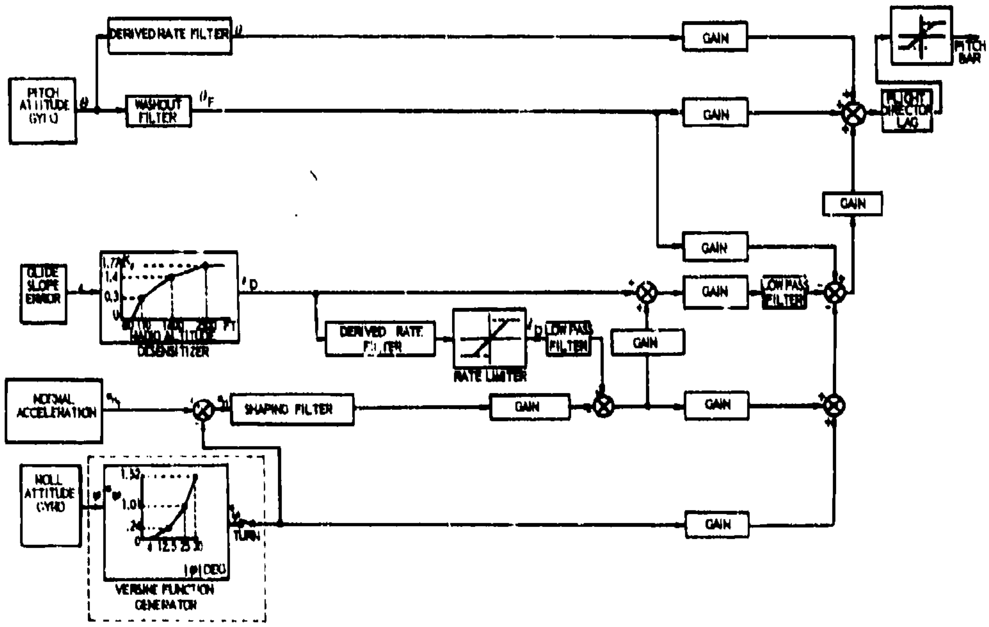
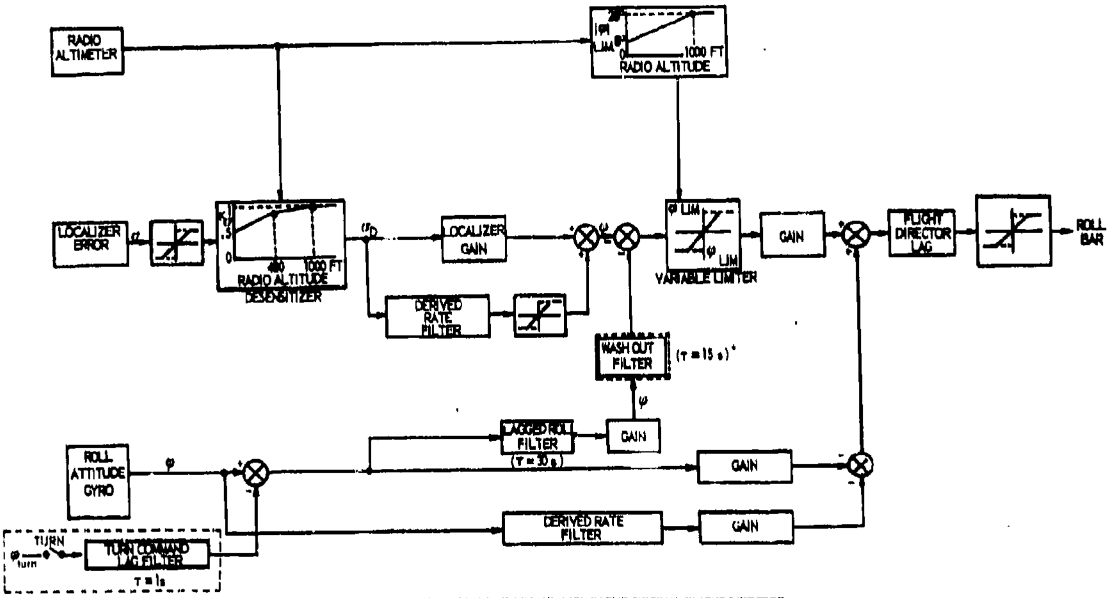


Fig. 6 Block diagram of simulated flight director pitch bar drive



*) A 60 s TIME CONSTANT WAS APPLIED IN THE ORIGINAL FLIGHT DIRECTOR

Fig. 7 Block diagram of simulated flight director roll bar drive

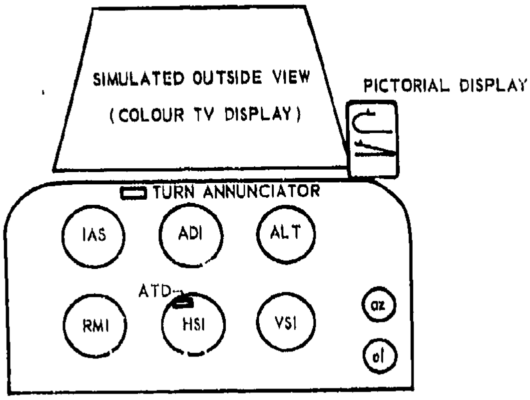


Fig. 8 The four degrees-of-freedom research simulator with single seat cockpit and collimating display

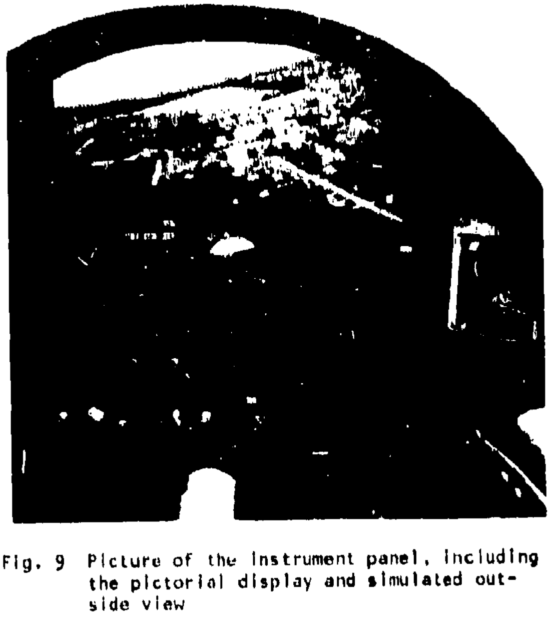
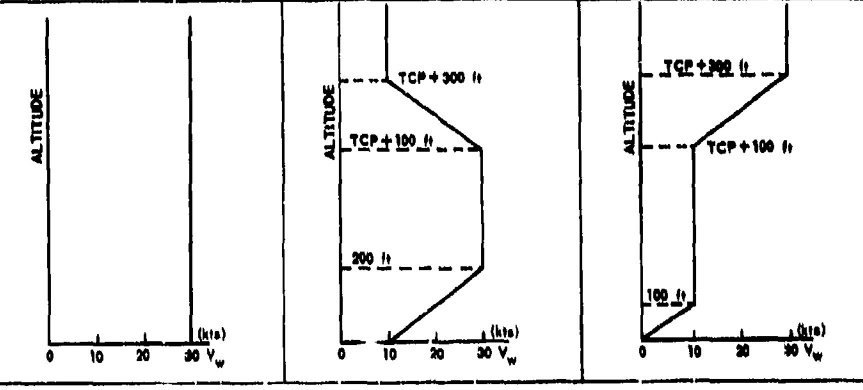
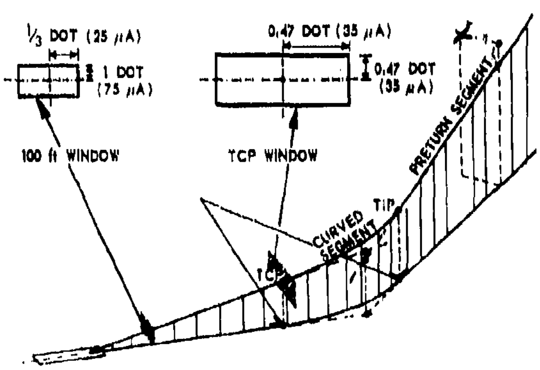


Fig. 9 Picture of the instrument panel, including the pictorial display and simulated outside view

	weather condition		
	W_1	W_2	W_3
cloud base*)	300 - 200 ft	~2000 ft	200 - 100 ft
RVR	700 m	> 10 km	400 m
wind direction	210°	210°	270°
turbulence	σ = 2 m/s ; F = 0.2	σ = 2 m/s ; F = 0.2	σ = 2 m/s ; F = 0.2
WIND PROFILE			

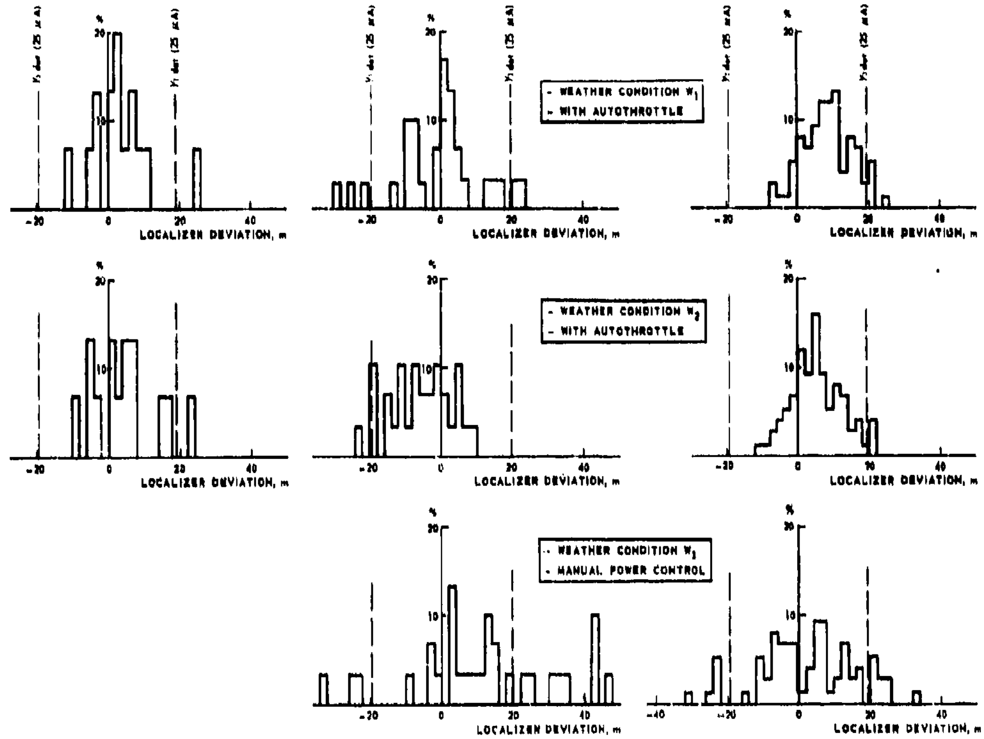
*) the first value for cloud base indicates the altitude at which the cloud break starts, whereas the second value shows the altitude where the clouds have been disappeared completely.

Fig. 10 Definition of the meteorological conditions



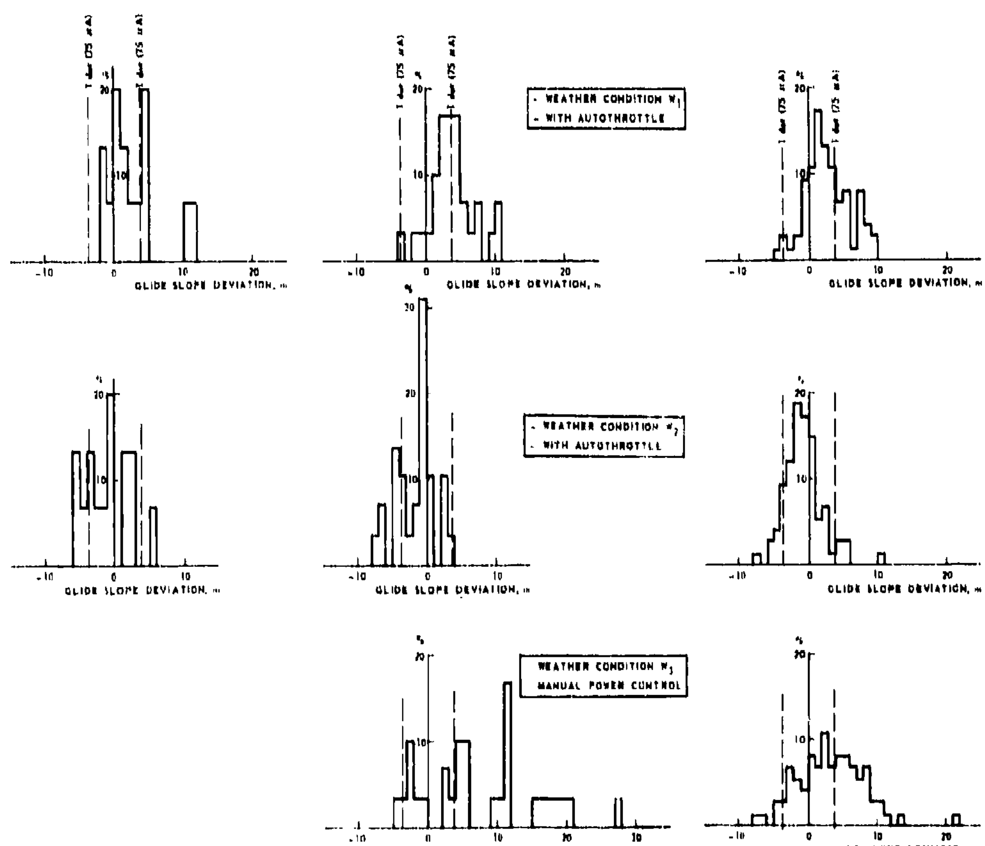
	WINDOW DIMENSIONS	
DATUM POINT	LOCALIZER DEVIATION	GLIDE SLOPE DEVIATION
100 ft	19.2 m	3.7 m
TCP		
122 m (400 ft)	38.9 m	6.8 m
305 m (1000 ft)	62.7 m	17.1 m
457 m (1500 ft)	82.6 m	25.6 m

Fig. 11 Position and dimensions of the 100 ft and TCP windows



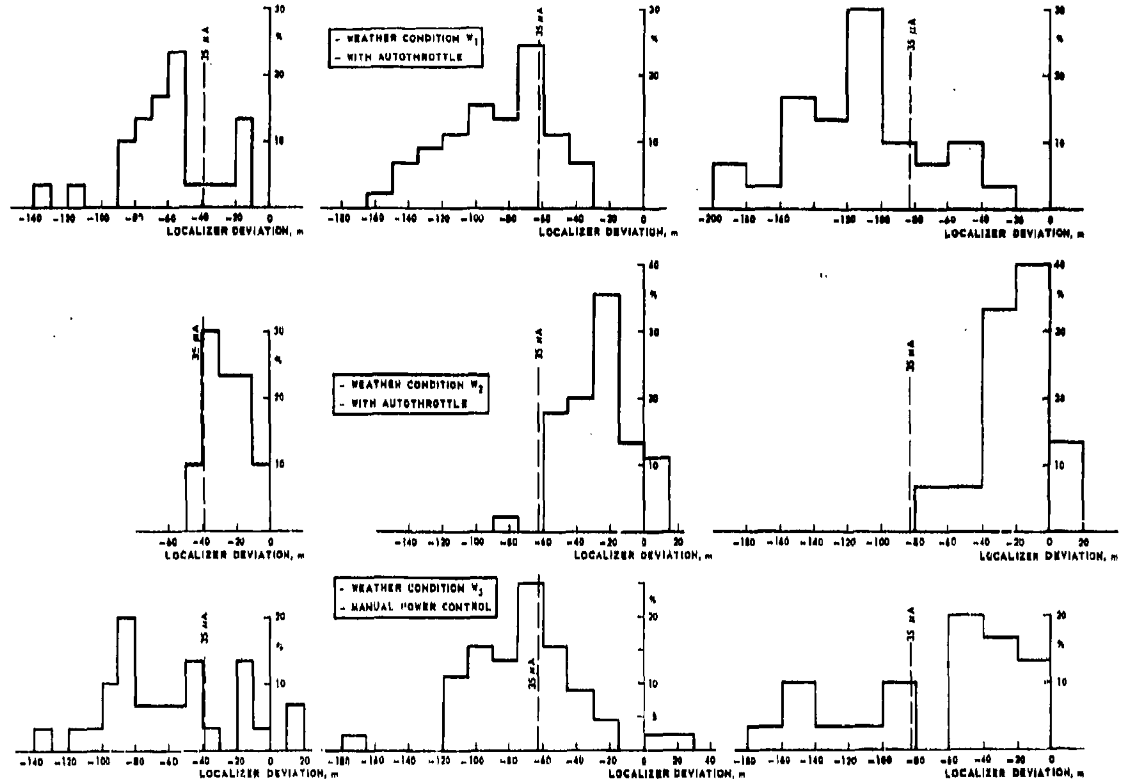
ILS type approaches   profiles 1 and 2   profiles 3 through 7

Fig. 12 Histograms of magnitudes of localizer deviation at the 100 ft point



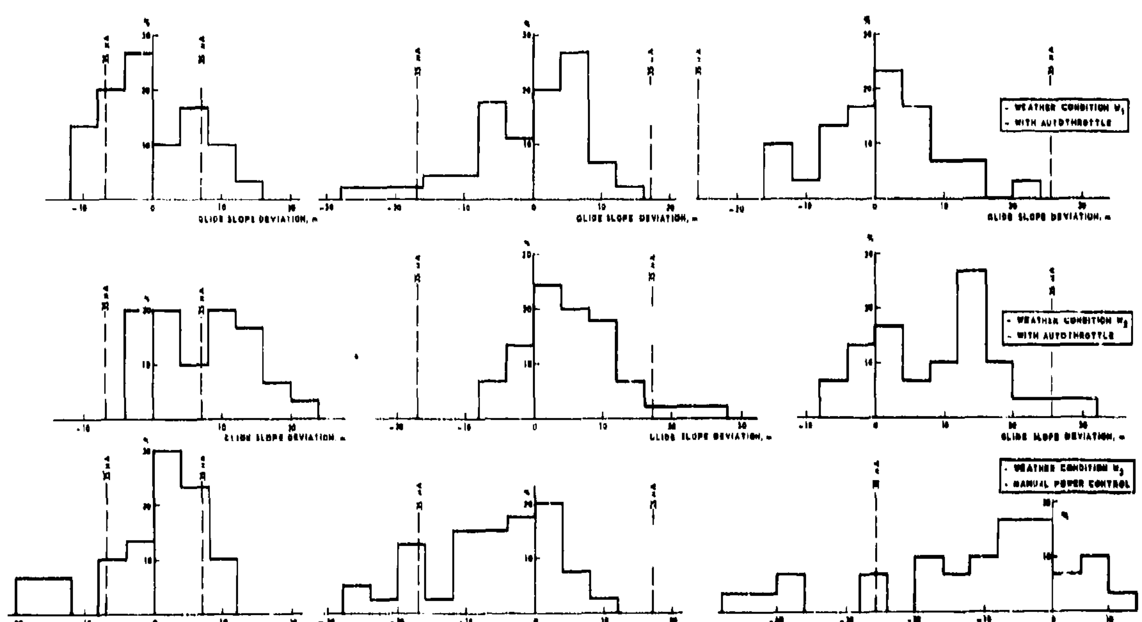
ILS type approaches   profiles 1 and 2   profiles 3 through 7

Fig. 13 Histograms of magnitudes of glide slope deviation at the 100 ft point



TCP at 122 m (400 ft) TCP at 305 m (1000 ft) TCP at 457 m (1500 ft)

Fig. 14 Histograms of magnitudes of localizer deviation at the turn completion point (TCP)



TCP at 122 m (400 ft) TCP at 305 m (1000 ft) TCP at 457 m (1500 ft)

Fig. 15 Histograms of magnitudes of glide slope deviation at the turn completion point (TCP)

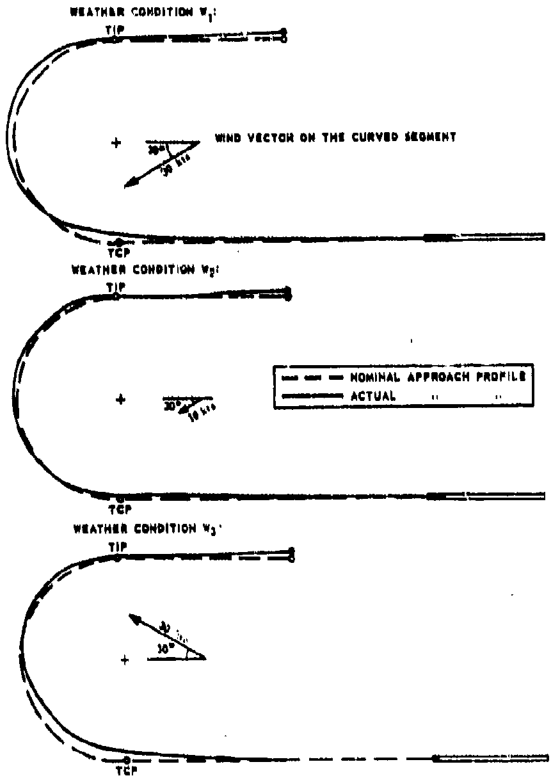


Fig. 16 Comparison between actual [illegible] nominal tracks for approach profile 7, showing the effect of the wind on the tracking accuracy on the curved segment

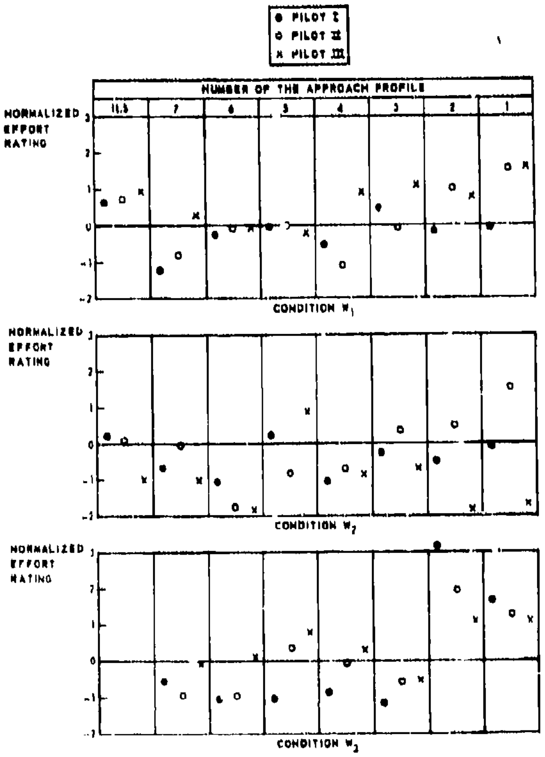


Fig. 17 Normalized effort ratings for the total approach execution

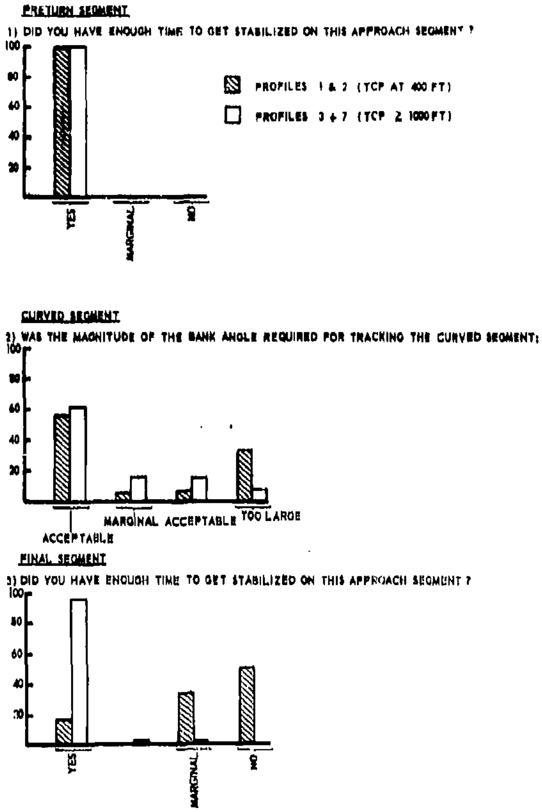


Fig. 18 Questionnaire results

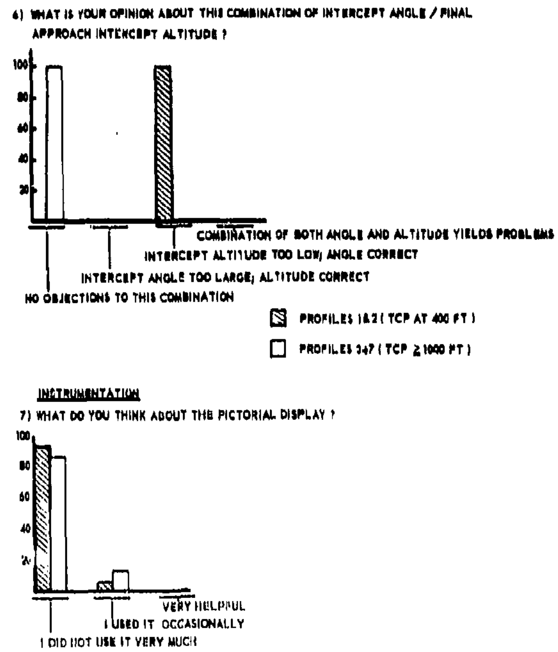


Fig. 18 Questionnaire results (Cont.)

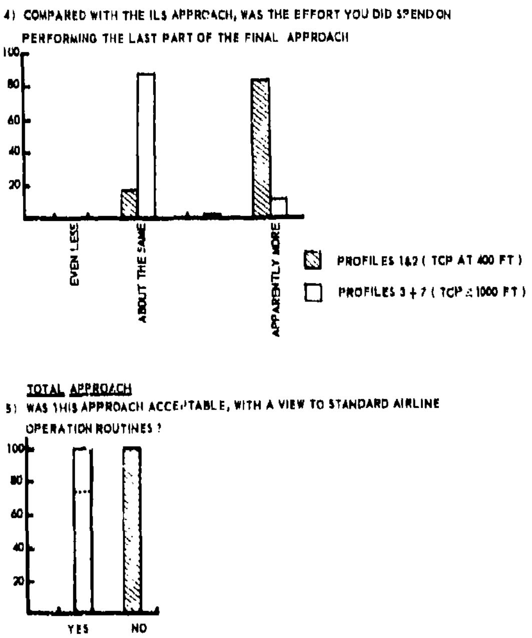


Fig. 18 Questionnaire results (Cont.)

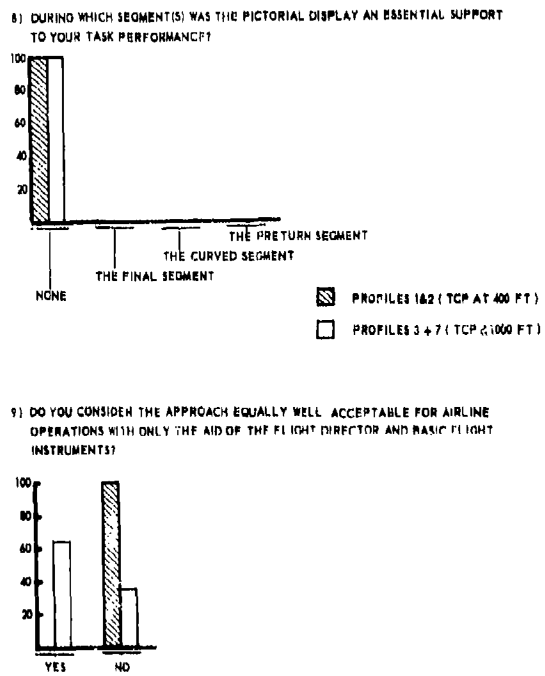


Fig. 18 Questionnaire results (Cont.)

MODELING AND FLIGHT SIMULATION OF AN ACTIVE CONFIGURED AIRCRAFT UNDER M.L.S. GUIDANCE

by

A.DANESI*, S.SMOLKA** and U.CHINAPPI***

I-SUMMARY

A new mathematical formulation is presented to integrate the differential equations modeling a vehicle automatically guided along a curvilinear trajectory by a microwave landing system. The augmented linear state equation, representing the open loop vehicle M.L.S. observer system, is given in standard phase variable form in which the altitude perturbations from the reference trajectory and numbers of its sucessive derivatives are assumed as state variables involved in a multi-feedback flight control system with gains fixed for a satisfactory vehicle transient behaviour in response to M.L.S. link-up commands. The state equation taken into consideration in system modeling will handle separately the transfer function characteristics polynomial while the dynamical effects of the system zeros are included in the algebraic output equation relating the actual altitude perturbations to the satate variables defined, in a rather fictitious fashion, in a state equation. The initial conditions to be imposed in the integration process must be consistent with the physical initial conditions on the actual trajectory considered in the problem at hand and for that purpose an original mathematical solution to the problem of transforming the initial conditions imposed on the physical state variables to the correspondent fictitious ones, is advanced. Using this transformation, easily performed with a numerical digital program, the phase variable system representation proves tobe very effective in trajectory simulation of a vehicle in which the input forcing function is defined in terms of the state variable constrained to the automatic flight control system. The proposed mathematical procedure results particularly useful treating with active controlled aircraft configurations as shown in the conclusive numerical application.

2- FUNDAMENTALS ON SYSTEM PHASE VARIABLE REPRESENTATION

Let an n-order linear system described by a differential state equation:

$$\dot{\underline{x}}(t) = A\,\underline{x}(t) + B\,u(t) \tag{1}$$

where the components of the n-state vector $\underline{x}$ (t) are stated as some particularly chosen output variable y(t) and its (n-I) sucessive derivatives i.e. :

$$\underline{x}(t) = \left| x_1(t), x_2(t), \ldots, x_n(t) \right| = \left| y(t), \frac{dy(t)}{dt}, \frac{d^2y(t)}{dt^2}, \ldots, \frac{d^{n-1}y(t)}{dt^{n-1}} \right| \tag{2}$$

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*Professor in the Aerospace School of Engineering-Rome University (Italy) and Visiting Professor at the Mech. and Aerospace Eng. Boston University,Mass. (U.S.A.)

**B.S. M.S. Associate Researcher at Mech. and Aerospace Eng. Boston Universit. Mass. (U.S.A.)

***B.S. M.S. Associate Researcher on Aerospace School of Eng.-Rome U. (Italy)

The components are consequently correlated by the differential relation:

$$x_i(t) = \frac{d\,x_{i-1}(t)}{dt} = \frac{d^{i-1}y(t)}{dt^{i-1}} \qquad (i = 1,2,\dots,n) \tag{3}$$

Consider the system transfer function:

$$G(s) = \frac{y(s)}{u(s)} = \frac{N(s)}{D(s)} \tag{4}$$

relating the Laplace transform of the output and control variable y(t) and u(s), where D(s) and N(s) are respectively the n-order characteristic polynomial and the m-order ($m < n$) numerator polynomial defining the system poles and zeros on the complex plane. At first N(s) is taken as an unitary scalar and using (3), the transfer function (4) is translated in the time domain yielding a differential state equation in phase variable form where the (nxn) state matrix A_f and the (nx1) control matrix B_f have the following structure:

$$A_f = \begin{vmatrix} 0 & 1 & 0 & \cdots & & & 0 \\ 0 & 0 & 1 & 0 & \cdots & & 0 \\ \hdashline 0 & 0 & 0 & 0 & \cdots & & 1 \\ -d_0 & -d_1 & -d_2 & -d_3 & \cdots & & -d_{n-1} \end{vmatrix}, \quad B_f = \begin{vmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{vmatrix} \tag{5}$$

In the last row of the matrix A_f appear the coefficients of the first (nx1) power in s of the characteristic polynomial D(s) with unitary coefficient for the n-th power in s. In the above stated hypotheses for N(s), the equation (I) in the state vector $\underline{x}$ (t) defined in (2) assumes the phase variable form with the state and control matrices given in (5) and strictly describes the dynamical effects of the system poles expressed in D(s). To put into consideration the numerator polynomial N(s) in this representation, the procedure adopted will arise from relation (4) equivalently modified in the following form:

$$G(s) = \left[\frac{\bar{y}(s)}{u(s)}\right]\left[\frac{y(s)}{\bar{y}(s)}\right] = G_1(s)\;G_2(s) = \tag{6}$$

$$= \left[\frac{1}{D(s)}\right]\left[N(s)\right]$$

Where $\bar{y}$ (s) is stated as the Laplace transform of a fictitious output variable which differs from the original output variable y (s) for the fact that it is involved only in the denominator dynamic. The fictitious transfer function:

$$G_1(s) = \frac{\bar{y}(s)}{u(s)} = \frac{1}{D(s)} \tag{7}$$

in the time domain is represented by the phase variable differential equation (1) where the state vector $\underline{x}$ (t) has to be referred to a fictitious output variable $\bar{y}$ (t) instead of the actual output variable y(t). The fictitious state variable for the equation (1) is defined:

$$\tilde{\underline{X}}(t) = [\tilde{x}_1(t), \tilde{x}_2(t), \ldots, \tilde{x}_n(t)] \equiv$$
$$\equiv \left[\bar{y}(t), \frac{d\bar{y}(t)}{dt}, \frac{d^2\bar{y}(t)}{dt^2}, \ldots, \frac{d^{n-1}\bar{y}(t)}{dt^{n-1}}\right] \tag{8}$$

The relation between the fictitious output variable $\bar{y}$ (t) and the actual one y(t) is obtained translating in time domain the fictitious transfer function:

$$G_2(s) = \frac{y(s)}{\bar{y}(s)} = N(s) \tag{9}$$

yielding the following algebraic output equation:

$$y(t) = C\,\tilde{x}(t) \tag{10}$$

where the components of the n-row vector C are the coefficients of the m-order $(m < n)$ numerator polynomial N(s) followed by zeros up to the system order, i.e. :

$$C = [n_0, n_1, \ldots, n_m, 0, \ldots, 0] \tag{11}$$

The phase variable differential equation (1) in the fictitious state vector x(t) (7) and the algebraic output equation (9) define completely the open loop system. The components of the fictitious vector $\tilde{x}(t)$ are supposed to be constrained to a multiple feedback branches through a n-vector feedback gain vector $\underline{K}_{fb}$ with values fixed to obtain a satisfactory behaviour of the actual output variable y(t) in response to an input forcing function. The mathematical representation of the system described by (1) and (9) in closed loop configuration is obtained adding the control law:

$$u(t) = K_s\,[r(t) - \underline{K}_{fb}\,\tilde{x}(t)] \tag{12}$$

where r(t) is a scalar input forcing function and K_s a forward gain as depicted in Fig. 1 where a phase variable feedback control system is represented. Substituting (12) in (1) yields the compact closed loop representation:

$$\dot{\tilde{x}}(t) = A_c\,\tilde{x}(t) + B_c\,r(t)\,,$$
$$y(t) = C\,\tilde{x}(t) \tag{13}$$

where:

$$A_c = A - K_s\,B\,\underline{K}_{fb}^T\,,$$
$$B_c = K_s\,B$$

Considering K_s and $\underline{K}_{fb}$ already known by computation, the closed loop system representation (13) is completely defined in terms of the coefficients of the denominator and numerator polynomial of the original transfer function G(s).

The integration of the differential state equation in (13) requires the knowledge of the initial condition vector $\tilde{x}$ (0) defined:

$$\tilde{x}(0) = \left[\tilde{y}(0), \frac{d\tilde{y}(0)}{dt}, \ldots, \frac{d^{n-1}\tilde{y}(0)}{dt^{n-1}}\right] \tag{14}$$

which is generally different from the physical initial condition state vector $\underline{x}$ (0):

$$\underline{x}(0) = \left[y(0), \frac{dy(0)}{dt}, \ldots, \frac{d^{n-1}y(0)}{dt^{n-1}}\right] \tag{15}$$

referred to the output vector $\underline{x}$ (t) describing the actual dynamic behaviour in the chosen primary controlled variable y(t).

The problem of transforming the actual set of the initial conditions (15) in the correspondent fictitious set (15) will be afforded in the next section.

3- INITIAL CONDITION TRANSFORMATION

The method presented in this section allows to transform the set of initial condition x(0) in the correspondent set x (0) referred to the closed loop state equation (13). The linear transformation :

$$\underline{x}(t) = L\,\tilde{x}(t) - T\,r(t) \tag{16}$$

was established differentiating (n-1) times the output equation (10) substituting for $\dot{\tilde{x}}$ (t) the right hand expression of the closed loop equation (13) and ordination the resulting terms after having defined a new n-input vector:

$$R(t) = [r_1(t),\ r_2(t),\ \ldots,\ r_n(t)]$$
$$= \left[r(t),\ \frac{dr(t)}{dt},\ \ldots,\ \frac{d^{n-1}r(t)}{dt^{n-1}}\right] \tag{17}$$

The (nxn) state transformation matrix L has the following structure:

$$L = [L_1 \mid L_2 \mid \ldots \mid L_n]$$
$$= [C^T \mid (A_c^T)\,C^T \mid \cdots \mid (A_c^T)^{n-1}C^T] \tag{18}$$

which results to be the system observability matrix. If no pole-zero cancellation occurs in the original transfer function G(s), that is the system is completely controllable, the matrix L will be not singular; in such hypothesis premultying both sides of equation (16) per the inverse of L yields :

$$\tilde{x}(t) = L^{-1}\,\underline{x}(t) + L^{-1}\,T\,r(t) \tag{19}$$

If the matrices L and T are given and the matrix L is not singular, the equation (18) allows to transform the vector x (t) in the correspondent fictitious vector $\tilde{x}$ (t). The control transformation matrix T is obtained defining the auxiliary n-row vector M :

$$M = [M_1 \quad M_2 \quad \ldots \quad M_{n-1} \quad 0]$$
$$= [K_sCB \mid K_sCA_cB \mid \cdots \mid K_sC(A_c)^{n-2}B \mid 0] \tag{20}$$

and constructing the matrix:

$$T = \begin{vmatrix} 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\ M_1 & 0 & 0 & \cdots & 0 & 0 & 0 \\ M_2 & M_1 & 0 & \cdots & 0 & 0 & 0 \\ M_3 & M_2 & M_1 & \cdots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & & \vdots & \vdots & \vdots \\ M_{n-1} & M_{n-2} & M_{n-3} & \cdots & M_2 & M_1 & 0 \end{vmatrix} \tag{21}$$

Imposing for $t(0) = t_o$ the following initial conditions :

$$R\ (t_o) = R\ (0) \quad , \quad \underline{X}(t_o) = \underline{X}(0)$$

the fictitious vector $\tilde{\underline{x}}$ (0) will be obtained using (19) now becoming :

$$\tilde{\underline{X}}(0) = L^{-1}\,\underline{x}(0) + L^{-1}\,T\,r(0) \tag{22}$$

For the common case where the system is initially not in forced state, that is :

$$\underline{R}(0) = 0 \tag{23}$$

the transformation (22) will be reduced in the form :

$$\tilde{\underline{X}}(0) = L^{-1}\,\underline{x}(0) \tag{24}$$

Applying the transformation (22) or (24) the closed loop state equation (13) may be integrated imposing as initial condition the computed state vector $\tilde{\underline{x}}$ (0) for which the state equation are written. The numerical computations involved in the linear transformation has to be performed by digital computer along with the observability check which is essential for the applicability of the present phase variable formulation. This program may be inserted as a subroutine in a general purpose integration program which will be entered in this case with the actual initial vector $\underline{x}$ (0)

4- PHASE VARIABLE MODELING OF ACTIVE CONFIGURED AIRCRAFT

The phase variable mathematical formulation given in the preceding sections is particularly useful in modeling active controlled vehicles where a number of aerodynamic effectors are employed to minimize the wing root banding moments in flight manouvers (2). In this case the state equation (1) is written for the open loop vehicle-autopilot system with the control matrix B sized (nxr) , where r is the number of the aerodynamic effectors involved in the vehicle active control.
The control matrix B is partitioned along columns,i.e. :

$$B = [B_1 \,\vdots\, B_2 \,\vdots\, \cdots \,\vdots\, B_i \,\vdots\, \cdots \,\vdots\, B_n] \tag{25}$$

where the i-th element B_i is the (nx1) control vector relative to the i-th aerodynamic effector asserved to one of the r-multichannels autopilot. Since the state matrix A is

common for all the channel equation, the mathematical analysis provided for the case m equal to one will be repeated for each i-th single channel considering the correspondent B_i element in the control matrix (25). The state variable equation pertaining to each channel may be written:

$$\dot{\underline{\tilde{x}}}_i(t) = A\, \underline{\tilde{x}}_i(t) + B_i\, u_i(t) \qquad (i = 1, 2, \dots, r)$$

$$y(t) = C_i\, \underline{\tilde{x}}_i(t) \qquad (i = 1, 2, \dots, r) \tag{26}$$

In figure 3 is given the symbolic state variable representation of a double channel system where the partial contribution of each single channel are summed to yield the global system response to the common forcing function r(t).
Writing the equation (26) in phase variable form, the control matrix B_i becomes equal for all channels, so this equation may be rewritten:

$$\dot{\underline{\tilde{x}}}_i(t) = A_f\, \underline{\tilde{x}}_i(t) + B_f\, u_i(t) \qquad (i = 1, 2, \dots, r) \tag{27}$$

In this equation the output vector C still appears to be different for each channel since the numerator polynomial N(s), reflecting the effect of the control terms, is different in each case.
Because of the system linearity and the particular phase variable structure of the equation (27), the contributions of all channel may be summed, and defining:

$$\underline{\tilde{x}}_T(t) = \sum_{i=1}^{r} \underline{\tilde{x}}_i ,$$

$$u_T(t) = \sum_{i=1}^{r} u_i(t), \tag{28}$$

$$y_T(t) = \sum_{i=1}^{r} y_i(t)$$

the following multi-channel state equation for the system depicted in Figure 4, was derived:

$$\dot{\underline{\tilde{x}}}_T(t) = A_f\, \underline{\tilde{x}}_T(t) + B_f\, u_T(t) \tag{29}$$

$$y_T(t) = C_T\, \underline{\tilde{x}}_T(t) \tag{30}$$

where:

$$C_T = \sum_{i=1}^{r} C_i = \left[\sum_{i=1}^{r} (n_0)_i \;\vdots\; \sum_{i=1}^{r} (n_1)_i \;\vdots\; \dots \;\vdots\; \sum_{i=1}^{r} (n_m)_i \;\vdots\; 0 \;\vdots\; 0 \right] \tag{31}$$

In (31) appear the coefficients of the numeratio polynomial N(s) defined for each control channel.
Observe that the feedback branches are originating from a point in the system where the signals are function only of the denominator dynamic which is common for all the channels; consequentely only a single feedback compensation through one forward gain is strictly necessary to control the transient behaviour of the multi-channel output system. Computing the forward gain K_s and the feedback vector $\underline{K}_{fb}$ in order to obtain a satisfactory behaviour of the multi-channel output variable y_T (t), the control law remain defined as:

$$u_T(t) = K_s\left[r(t) - \underline{K}_{fb}^T \, \underline{x}_T(t)\right] \tag{32}$$

Substituting (32) in (28) yields the multi-channel closed loop state equation:

$$\dot{\tilde{\underline{x}}}_T(t) = A_c \, \tilde{\underline{x}}_T(t) + B_c \, r(t) \tag{33}$$

$$A_c = A_f - B K_s \underline{K}_{fb}^T \tag{34}$$

$$B_c = K_s B_f \tag{35}$$

with the output variable y_T (t) expressed by (30). The state equation (33) may be integrated imposing the initial condition:

$$\tilde{\underline{x}}_T(0) = \tilde{\underline{x}}_{T_0}$$

obtained by the actual initial condition:

$$\underline{x}_T(0) = \underline{x}_{T_0}$$

applying the linear transformation introduced in section 3.

5- M.L.S. TRAJECTORY SIMULATION

The ground derived microwave landing system applies to the automatic flight control system input the polar coordinates of the reference trajectory fixed by the air traffic control center. In the longitudinal plane these are the elevation angle (α_D) and the distance R_D from DME station. The polar coordinates (α_D, R_D) may be substituted by the actual altitude h_D in respect to the M.L.S. reference plane.
Simultaneously with these information the M.L.S. stations (EL-I for the initial approach segment and EL-2 for flare control- see (3)) provides the emission of the correspondent desired altitude function h_D (t) in the aircraft point position. All these in-

formations are sent via multi-plexed ground-air linking; in this functions the M.L.S. system acts as an observer of the vehicle motion in the longitudinal plane like a physical sensor in a feedback system measuring the same vehicle output variable observed by the M.L.S. system while the desidered coordinate is applied to the autopilot input to form the actual error existing in following the desidered trajectory. In this sense the M.L.S. transfer characteristics can be included in a feedback loop enclosing the vehicle-autopilot mathematical model in the forms (33). Generally the M.L.S. observer transfer function $G_O(s)$ is positioned in the system forward loop adding a prefilter ahead the autopilot summing point to maintain the system equivalence and aggregating to it the M.L.S. - Autopilot Coupler transfer function $G_M(s)$ as depicted in Figure 5. The forward loop transfer function hence becomes:

$$G_f(s) = G_M(s)\, G_o(s)\, G_A(s) \tag{36}$$

where $G_A(s)$ is the closed loop autopilot-aircraft transfer function selected for the output variable:

$$y(t) = h(t) \tag{37}$$

In the M.L.S. lateral guidance mode the polar coordinate are the azimuth angle ψ and the distance R from D.M.E. station or the resulting distance y(t) from a reference vertical plane containing the runway centerline. In both cases the open loop system will be closed by an ideal unitary feedback which represent the M.L.S. observer link-up. Deriving the forward transfer function in phase variable form as indicated in the preceding sections the output equation will take care of the selection of the chosen output variable as primary variable in the trajectory simulation. The correspondent input forcing function which describes the desidered trajectory to be followed by the vehicle on the entire landing procedure, will be applied to the summing point of the ideal feedback closure transducing the actual trajectory information from the M.L.S. stations.

The global system representation is given in Fig. 5 where the closed loop autopilot-vehicle-M.L.S. observer system appears to be forced by the control law:

$$u(t) = K_R\, h_D(t) - h(t) \tag{38}$$

6- NUMERICAL APPLICATION

The generalized digital program given in Ref. (1) which includes the initial condition state transformation subprogram has been employed to simulate the M.L.S. trajectory in a vertical plane of a configured aircraft treated. The vehicle is a large body transport aircraft for which two aerodynamic effectors moved by an optimized flight control system were provided to minimize wing bending moments in flight maneuvers performed using the elevators as primary longitudinal flight controls. The automatic flight control system is supposed to operate as a multi-feedback control system in which the altitude h(t) is considered as primary constrained variable. The altitude perturbations due to the controls application and the dynamic effects of the actuating servosystem and M.L.S. Coupler are described by the transfer function of the type (36) :

$$G_f(s) = \frac{h(s)}{U_i(s)} = \frac{N_i(s)}{D(s)} \quad , \quad i = (1,2,3) \tag{39}$$

where the second order denominator polynomial $N_i(s)$ aredefined for each of the three controls involved in the longitudinal maneuver, i.e. the elevators and the two active effectors. The coefficients of the fifth order characteristic polynomial $D(s)$ appear in the last row of the state matrix A for the system described in phase variable form as given below :

$$A = \begin{vmatrix} 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 & 0 \\ 0 & 0 & 0 & 1.0 & 0 \\ 0 & 0 & 0 & 0 & 1.0 \\ 0 & -3.656 & -8.03755 & -17.53 & -20.86 \end{vmatrix}$$

Taking into account the multi-channel structure of the treated active control system, the state equation will be written as in (29) where the output vector C_T is obtained applying the relation (31). Performing the operations involved in this expression yields:

$$C_T^T = [-371.61,\ 30.5028,\ 72.0,\ 0,\ 0]$$

The autopilot forward gain K_s and the feedback vector $\underline{K}_{fb}$ were computed in order to obtain a satisfactory short period system transient behaviour to step input command resulting in:

$$\underline{K}_{fb}^T = [-371.61, -978.016, -489.197, -108.87, -4.3]$$

$$K_s = -4.604$$

Using the above given data the system closed loop state equation (33) become available to be integrated for trajectory study purpose. A typical M.L.S. landing procedure with multi-slope trajectory in a vertical plane was provided for a digital simulation carried out with the generalized numerical program given in Ref. (1). The initial conditions were fixed at the trajectory point where the vehicle is crossing the approach procedure gate in a steady rectilinear flight path with a slope of four degree. The vector of actual initial condition was established as follows :

$$\underline{X}_0^T = [304.8,\ -3.14,\ 0,\ 0,\ 0]$$

The fictitious initial condition vector $\tilde{\underline{x}}(0)$ is computed by the subroutine which is a part of the main integration program (1) and the result is printed in the program output.

$$\tilde{\underline{X}}_0^T = [-1.092,\ 0.822,\ -1.748,\ 4.9,\ -11.098]$$

The forcing function applied to the unitary feedback closed loop system depicted in Fig. 5 is representative of the trajectory commanded by the M.L.S. link-up multiplexing which are supposed to obey in sequence the following desidered altitude $h_D(t)$ law :

I- For the intermediate approach segment (γ = 4°)

$$t_0 \leq t < 45.6 \text{ (sec)} \quad : \quad h_D(t) = 304.8 - 5.65\,t$$

2- For the final approach segment (γ = 2,5°)

$$45.6 < t \leq 55.7 \text{ (sec)} \quad : \quad h_D(t) = 190.1 - 3.14\,t$$

3- For the automatic exponential flare maneuver:

$$t > 55.7 \text{ (sec)} \quad : \quad h_D(t) = 15.24\, e^{-0.3t}$$

The exponential trajectory is supposed to be tangent to the horizontal plane located at 7.332 meters below the runway level to allow for a desidered aircraft sink speed (1.02 m/sec) at the ground contact.

The autothrottle control is supposed to keep constant the air speed at the value of 72 m/sec along all the considered landing trajectory.

Considering at the initial time the desidered altitude and vertical speed coincident with the actual flight values the condition (23) on the initial unput vector R(0) applies so the simplified linear transformation (25) is automatically chosen inside the integration program imposing R(0) equal to zero as input data.

In order to have an enlarged view of the dynamical behaviour of the aircraft in the terminal flare maneuver the closed loop system equation was integrated supposing as actual initial condition vector:

$$\underline{X}_0^T = [\,15.24,\ -3.14,\ 0,\ 0,\ 0\,]$$

with the correspondent fictitious vector resulting :

$$\tilde{\underline{X}}_0^T = [\,-0.0482,\ 0.0306,\ -0.0503,\ 0.1357,\ -0.3172\,]$$

The graphic results printed at the program output show in Fig. 6 the complete desired and actual trajectories marked respectively with "R" and "T" letters while the curve identified by letter E gives the altitude error existing in following the desired trajectory. In Fig. 7 the same representation is given for the flare portion of the landing trajectory.

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[2] DANESI, A and SMOLKA, S, oth., "Trajectory behavior of control configured aircraft subject to random disturbance", Agard Conference on Aerodynamic characteristic of controls", Preprint No. 262, 1979.

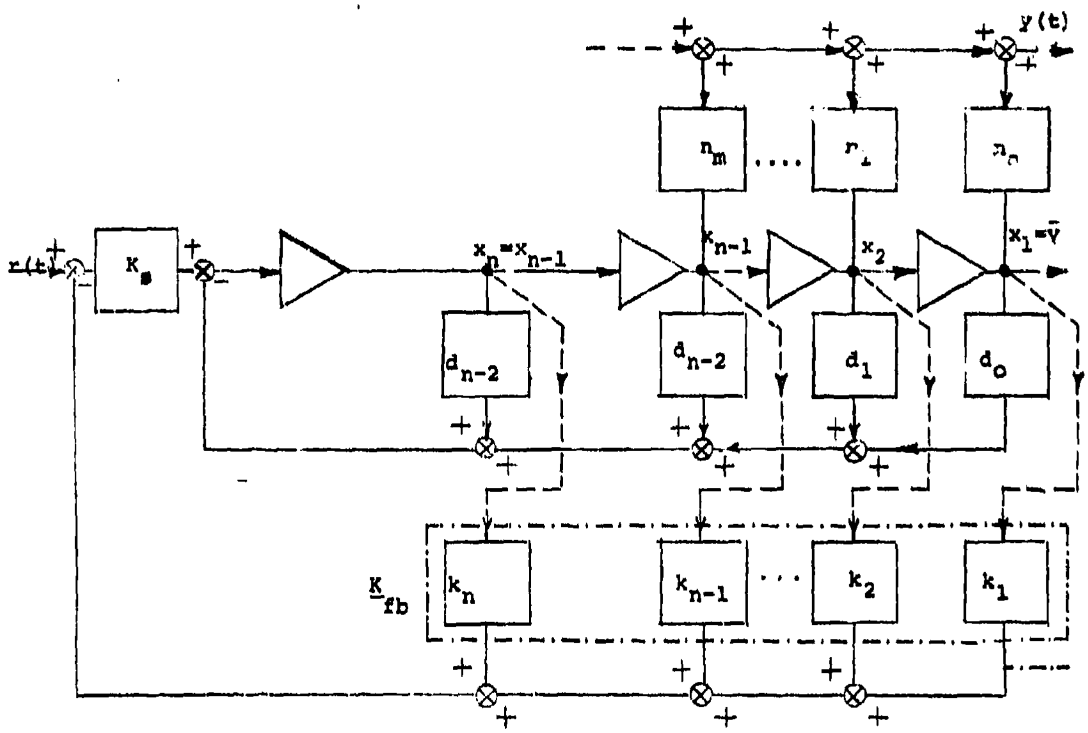

Fig.1-Analogic scheme of a phase variable feedback control system

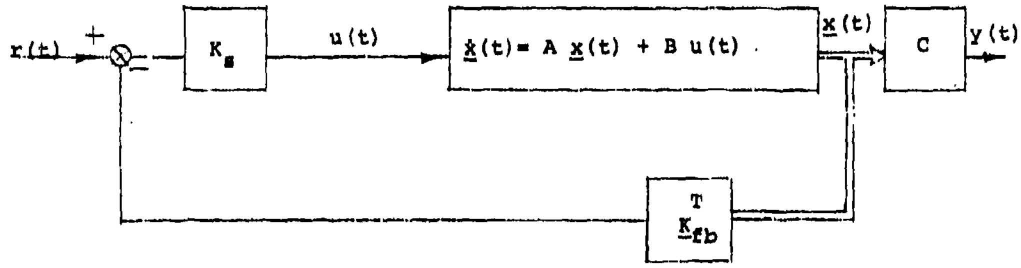

Fig.2-Symbolic phase variable representation of feedback control system.

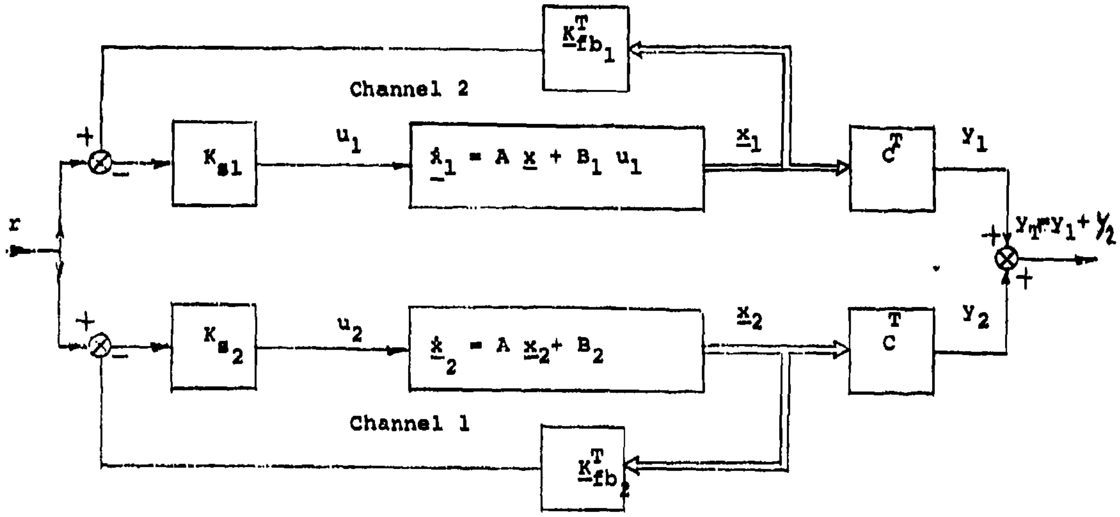

Fig.3- Double channel system in state variable representation

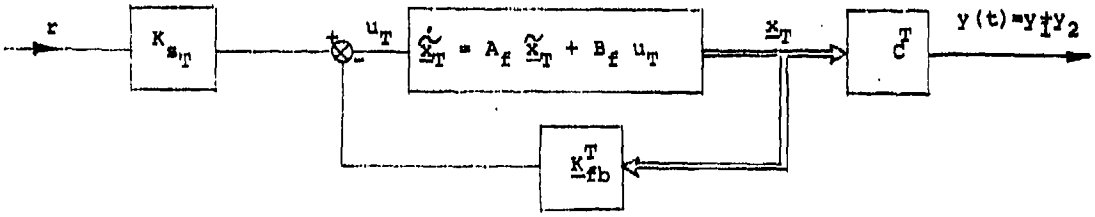

Fig.4- Double channel system in phase variable representation

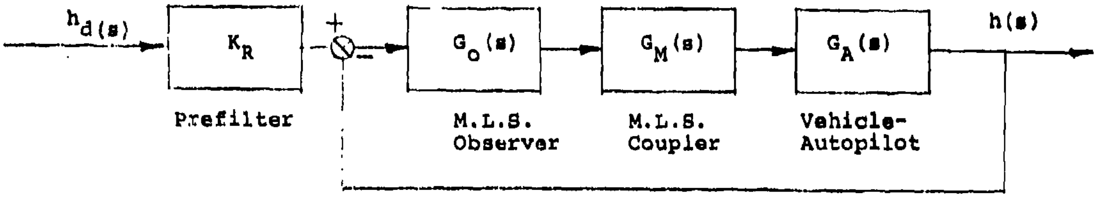

Fig.5- System considered in digital simulation

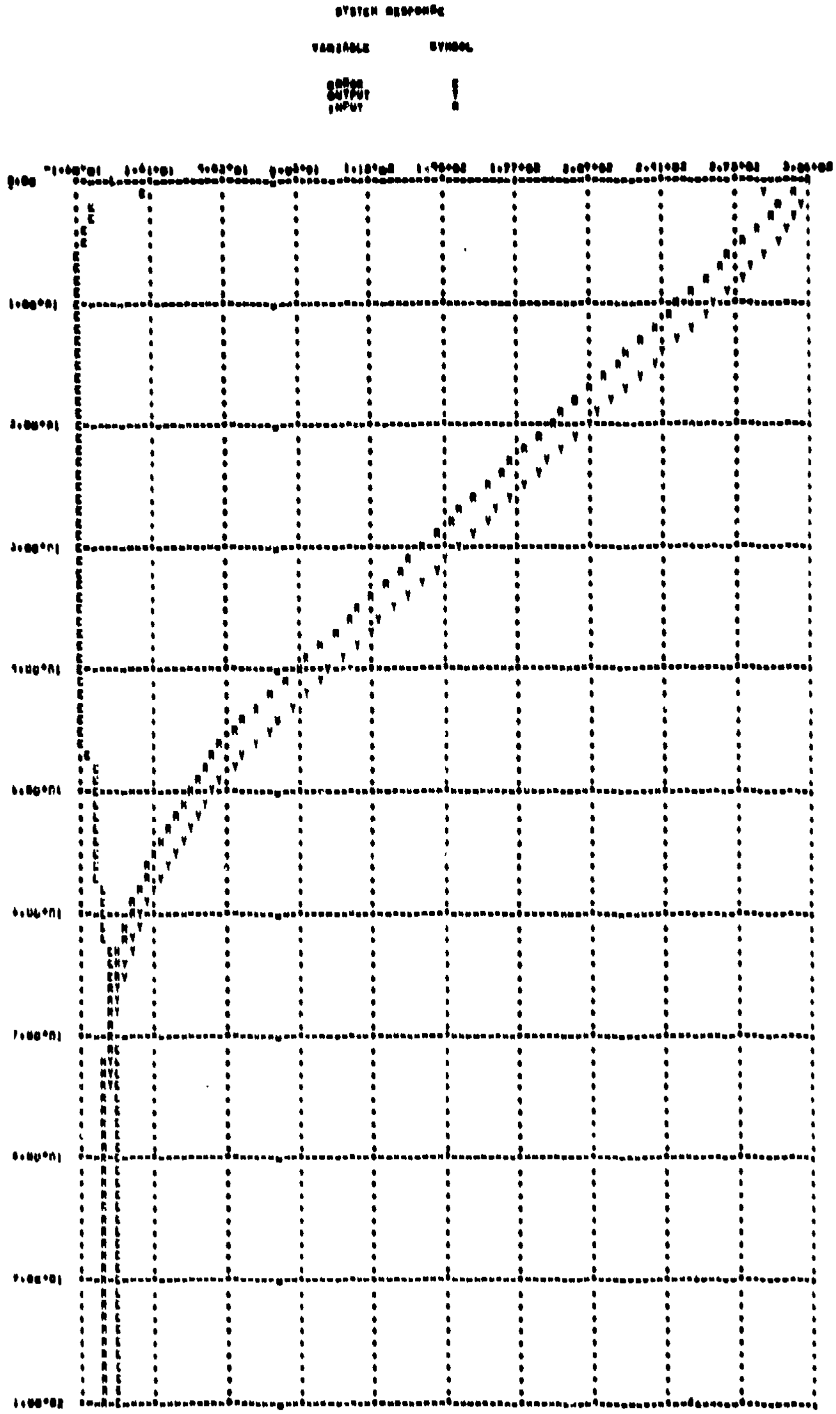

Fig.6- complete M.L.S.landing trajectory simulation

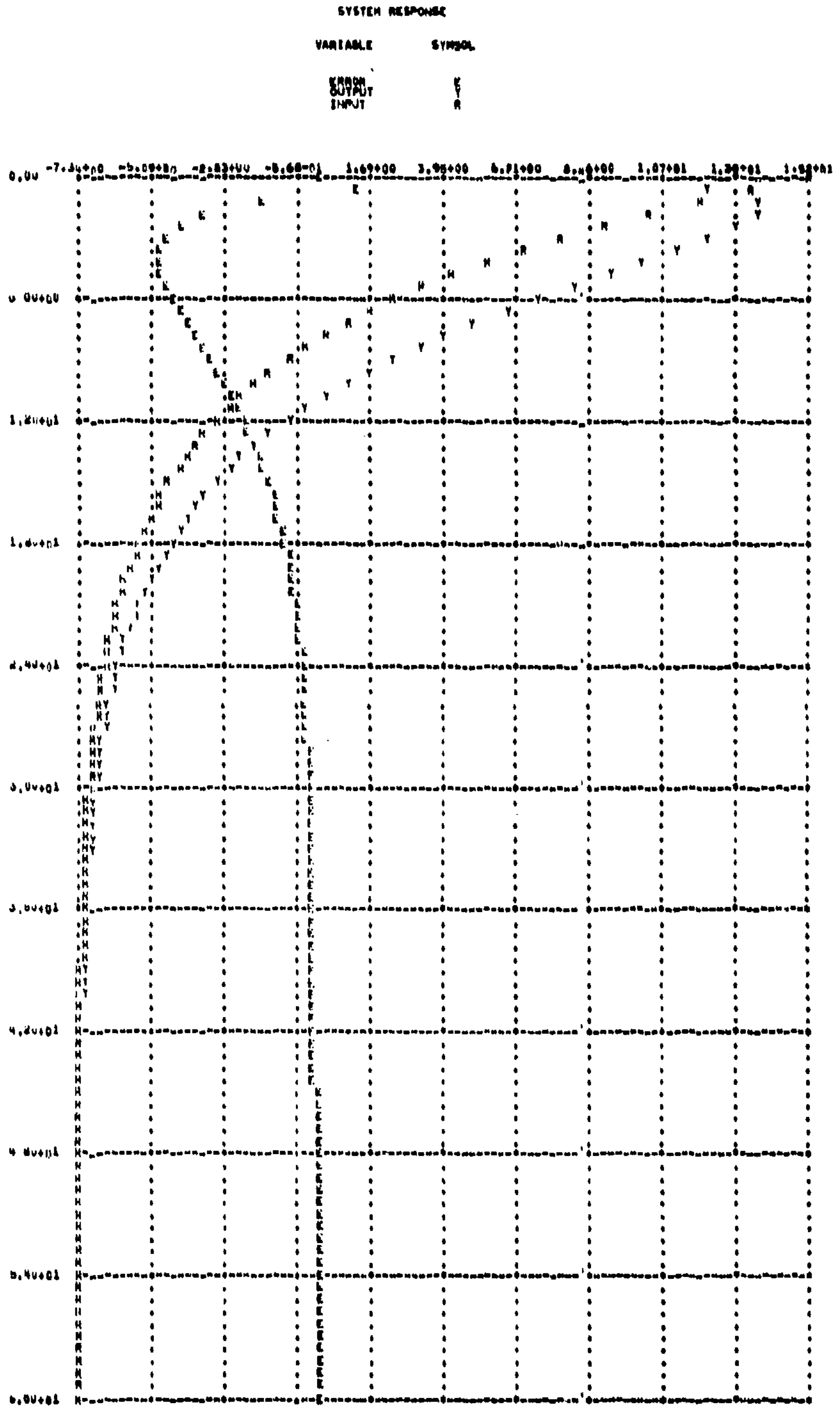

Fig.7-M.L.S.flare trajectory simulation computer result.

SYMBOLISM

A = State matrix

B = Control matrix

C = Output vector

D(s) = Characteristic polynomial

G(s) = System transfer function

$G_1(s)$ = Fictitious transfer function relative to the denominator dynamic

$G_2(s)$ = Fictitious transfer function relative to the numerator dynamic

$G_A(s)$ = Closed loop aircraft-autopilot transfer function

$G_F(s)$ = Overall forward transfer function

$G_M(s)$ = M.L.S. Coupler transfer function

$G_O(s)$ = M.L.S. Observer transfer function

L = Initial condition state transformation matrix

N(s) = Transfer function numerator polynomial

M = Auxiliary vector in the initial condition transformation

K_R = M.L.S. Receiver gain

K_{fb} = Feedback gain vector

K_S = Forward loop gain

T = Initial condition control transformation matrix

R = Input forcing function vector

d_i = Characteristic polynomial coefficient

n = System order

n_i = Numerator polynomial coefficient

m = Numerator polynomial order

q = Pitch rate

r = Number of autopilot channels

s = Laplace operator

u = Scalar control variable

$\underline{x}$ = System state vector

y = Output variable

MODELING THE HUMAN OPERATOR: APPLICATIONS TO SYSTEM COST EFFECTIVENESS

By

Norman E. Lane, Commander, USN
Naval Air Development Center

Melvin I. Strieb
Analytics, Inc.

Walter Leyland
Naval Air Development Center

Most attempts to improve overall system performance in modern air weapon systems result in changes to avionics hardware and software. Such changes are designed to enhance system capabilities in data processing, in accuracy and quality of data inputs/outputs, and in the classes of information available to the operator. However, as the interdependence of system components adds complexity, it can no longer be assumed that avionics modifications will result in actual improvement in system performance. The ability of the operator to use new system features must be considered in determining their value. Total system performance may increase only minimally or even decrease if information provided is not relevant to the operator's requirements or if current task loading precludes timely application of information. When system performance is not enhanced by a modification, both the intended purpose and the cost effectiveness of the system is significantly degraded. Previous approaches to predicting system effectiveness have focused primarily on hardware and software modeling without inclusion of realistic operator/system interactions. The technique described in this paper, Operator Interface Cost Effectiveness Analysis (OICEA), represents an initial attempt to overcome this limitation. The methodology combines system modeling with cost projections to evaluate the cost benefits of alternative proposed designs within appropriate mission contexts. Major avionics variables are integrated into a cohesive approach which simulates hardware and software functions and the performance of an operator interacting with these components, using a model called the Human Operator Simulator. OICEA allows for systematic variation of key factors that influence effectiveness, including degree and type of task automation, equipment and human reliability, scenarios and tactical doctrine and operator characteristics. This paper summarizes the OICEA methodology and documents applications to avionics and sensor improvements on a fixed wing antisubmarine warfare platform.

INTRODUCTION

Modern air weapon systems must respond to continually changing threat conditions. Each new threat can give rise to the need to modify and update the avionics hardware and software in current systems. With the increasing costs of these changes and the increasing need to demonstrate return on investment, techniques have been developed in recent years to estimate the impact on system performance of proposed updates. These predictions of future effectiveness, usually obtained through computer modeling of all or part of the system, have involved the implicit assumption that increasing system capabilities will yield a direct and comparable increase in system performance. Experience with the use of new and updated systems in the fleet has indicated that this assumption is not always tenable. Forecasts of system performance from conventional hardware and software models have overlooked an important system component -- the operator. In particular human limitations impose a major constraint on the utilization of system improvements.

Avionics modifications usually involve either new hardware or new software that increase the degree and quality of automation, or improvements in the accuracy and sensitivity of sensor information and other system input/output data. Conventional methods of performance estimation have either ignored the operator or have used simple transfer function representations, without an adequate understanding of the limits within which these functions are applicable. As systems have increased in complexity, it is no longer adequate to assume that automation will necessarily produce increases in performance. Inappropriate automation may, in fact, have the opposite effect. We can no longer assume that by giving the operator more sophisticated data, system performance will automatically be improved. Additional or more refined sensor data, for example, will not improve performance if it is received during periods of heavy operator loading or if the data exceeds the precision which the operator needs to perform a given function. Proposed system changes must therefore be evaluated by considering how well an operator can make use of the new capabilities provided by the proposed changes. Evaluation techniques that do not consider this factor in their estimates will be in error; as operator loading approaches saturation, such estimates will become wildly optimistic.

Designers of current and future weapon systems must cope with several harsh realities that constrain available design options. First, funds for development and deployment of systems are becoming limited; pressures are mounting for more cost-effective utilization of fiscal resources. Design decisions must be made on the basis of maximum contribution to the defense mission for each dollar invested. Second, the human is no longer a low-cost component of systems; skilled manpower is becoming an increasingly scarce

commodity. The effective use of available manpower must be a primary consideration in the selection of design options; new systems must make effective compromises between the use of man and use of equipment to accomplish system functions, with cost-effectiveness as a major criterion for choosing between design alternatives.

The critical role the operator plays in systems effectiveness, in combination with the fiscal and manpower constraints discussed above, indicate the need for a new evaluation technique. The method must provide realistic estimates of the configuration's performance, with operators of varying ability. Such information, when combined with appropriate cost data, will permit choice among alternative design configurations on the basis of expected performance relative to expected cost.

Operator Interface Cost Effectiveness Analysis (OICEA) represents an effort to develop such a cost-effectiveness prediction methodology. The approach is based on the Human Operator Simulator (HOS) model (Strieb, 1975; Wherry, 1976), developed for evaluating system operability during early system design. The following sections present the OICEA methodology and its rationale, summarize features of the HOS model and describe two applications of the technique. The first application deals with the non-acoustic sensor station operator on an antisubmarine warfare (ASW) patrol aircraft; it compares a current system with several alternate configurations and demonstrates that OICEA can identify known problems and diagnose their causes. The second application, in progress, simulates the acoustic sensor station operators in an advanced (not yet operational) version of the same ASW aircraft. The simulation models avionics that include a highly advanced onboard signal processor and newly developed acoustic sensors. The goal of this application is to identify potential problems prior to fleet introduction and to provide a readily available mechanism for evaluating and correcting system deficiencies ected during operational use.

APPROACH

Rationale

Differing system configurations that may vary widely in their actual operational effectiveness may appear to be virtually indistinguishable during early development stages. It is normally prohibitively expensive to develop a hardware simulator or prototype for each alternative in order to obtain an estimate of its potential worth. Therefore, there is a requirement for a methodology to assist early in the system design process in determining the alternatives to be retained for development. Digital computer modeling has been a traditional and typically effective method for making forecasts under such conditions. The OICEA technique combines digital computer equipment and operator models with standard costing techniques to obtain data that enables alternatives to be compared with one another and with existing systems on the basis of cost effectiveness.

Any model that is to be used to perform such an evaluation must satisfy several criteria:

- First, it must be integrative. It must be able to simulate the hardware, software, and operator system components within a single conceptual framework, along with any external data sources such as sensor data returns and communications.
- Second, the model must be flexible; it must be able to accommodate virtually any class of manned system or subsystem and provide for straightforward modification of system characteristics without extensive revisions.
- Third, it must be sensitive to relatively subtle differences in configuration performance. This presupposes a level of detail in the model consistent with the use of task or subtask level analytic data for operators and detailed specifications for the equipment.
- Fourth, the model must be dynamic reallocating its task priorities in accordance with performance influences which may be exclusively situation-dependent.
- Fifth, the model must be parametric. Many of the quantities which describe operator capabilities and performance characteristics of equipment are not fixed values, but can vary both between and within operators and between and within hardware/software configurations. Iterating a simulation with different values of potential key parameters can help to determine which of these particular parameters are important and which parameter values provide the best performance. Varying such quantities as sensor return integration times, radar detection ranges, and operator characteristics can yield valuable information both about design and training questions and about system effectiveness.
- Sixth, the model must be able to produce specific quantitative measures of system performance. There are, for any system, numerous ways of deriving numbers which reflect performance. The combination of measures into a single global assessment of performance must eventually entail obtaining explicit judgements of worth or utility for each of these effectiveness measures. The model must enable the estimation of separate performance indices that are specifically quantifiable and mission-relevant. Variables such as time to perform a mission, ordinance or stores expended, number of correct ship/aircraft identifications, and targets processed or probable kills are all potential numerical reflections of system success. While the measures will change from one system to another, effectiveness indices should be readily obtainable from routine model outputs.

The Human Operator Simulator(HOS)

HOS is a digital computer program designed to simulate the complex interactions between man and equipment by modeling both the operating characteristics of the machine and the perceptual, cognitive and motor functions of the operator. HOS is a "generalized operator." It becomes a specific operator in a specific situation when it is provided with descriptions of the equipment to be used and the procedures to be followed. Procedural instructions are written in the Human Operator Procedures Language (HOPROC), a simplified English-like computer language; operator transfer functions or mathematical expressions of hardware functioning within a procedure may be represented in FORTRAN, a subset of HOPROC.

HOS differs from other models of operator functioning in that times for task execution are not supplied by an analyst or drawn from sample time distributions. Instead, HOS generates task performance data in accordance with detailed human performance micromodels built into the HOS system. The HOS operator is capable of performing seven "primitive" functions:

- obtaining information,
- remembering information,
- performing mental calculations,
- making decisions,
- moving a body part,
- manipulating a control,
- relaxing.

Every action that the HOS operator performs is a combination of one or more of these primitive functions. Internal decision rules within HOS automatically determine the function combinations that make up a task, determine the sequence in which tasks are performed, and calculate the time required to complete them.

The detailed analysis of system events is performed by another program, the Human Operator Data Analyzer and Collater (HODAC), which provides information on operator activities and equipment status at any instant in time during the simulation. HODAC generates statistics on operator time usage during a mission, the sequences of processes executed, the frequency and total time spent in accessing each control and display, and other summary reports.

HOS has several sophisticated features that make it particularly applicable to the simulation of complex missions. For example, the HOS operator is goal-oriented; that is, the operator will perform actions necessary to accomplish a task, but will omit actions that have become unnecessary due to events elsewhere in the simulaton. In addition, formal strategies or decision rules supplied by the analyst may employ branching logic that may be dependent on system status at the time the decision must be made. The task-sequencing algorithms in HOS are dependent on an original procedure priority (set by the analyst) modified by the time since that procedure was last executed. For procedures which involve reading displays, control manipulation, or instrument monitoring, priorities are also modified by an "internal limits" factor which specifies the degree of precision required for that operation. Procedures with small internal limits that must be executed more often have their priorities changed accordingly. Based on all these factors, computed priorities are compared and the most critical procedure is executed.

Parameters describing operator characteristics can be provided to the simulation to vary the charteristics of the HOS operator. The default values of these parameters are chosen to represent a trained operator with "average" abilities. The HOS operator will perform assigned tasks with little or no chance for error unless that error is specifically introduced and controlled by the analyst. This power to control the characteristics of the operator provides a ready method of determining the range of operator abilities for which a system is suitable.

HOS has been used to simulate a variety of relatively simple tasks such as reach performance, multiple dial reading and mail sorting (Strieb, 1976). It has been applied to assessment of operator workload in a dual task situation (Lane, Strieb and Wherry, 1977) and to a complex operational mission -- a simulation of the Air Tactical Officer in the LAMPS antisubmarine helicopter (Strieb et al, 1975). HOS is described in more detail in Strieb, Glenn and Wherry (1978). Useful analyses which discuss HOS in the context of other operator models are contained in Pew et al (1977) and Greening (1978).

Operator Interface Cost Effectiveness Analysis

The approach to system evaluation described in this paper is not a new model. Rather it is a way of using existing models to organize and answer questions about new systems or alternative designs. The goal is to provide the best possible projections of the performance of those alternatives within the range of conditions likely to be encountered in fleet use.

Systems are rarely manned by perfect operators. While it is important to know the performance potential of a system with an operator who is capable of handling every conceivable task in every conceivable situation, it is much more critical to understand the probable performance given a typical operator with human limitations in realistic situations. It is not uncommon for substantial research and development costs to be invested in a system which performs more poorly than a system already in the fleet. Some new

systems achieve distinct improvements in performance, but only with an unacceptable level of operating and support costs.

New systems must be designed to provide improved performance at a reasonable cost. Frequently however, a consistent set of criteria are not considered when choosing among the various available ways of improving system performance. The objective of the OICEA approach is to make criteria directly visible by the deliberate comparison of alternatives to a baseline performance level and a baseline cost. OICEA is the systematic application of digital simulation to derive performance/cost data as early as possible in the design cycle. Generally, this involves:

- simulating a baseline system;
- simulating one or more system alternatives;
- obtaining appropriate performance measures for baseline and alternatives;
- obtaining baseline and alternative cost data;
- generating cost/benefit tradeoffs based on these data.

To achieve a breadth of comparison using prototypes, dynamic simulators or functioning mockups would require excessively heavy investments of time and dollars, and results would be too late to impact on system selection. OICEA enables performance estimates to be derived quickly and inexpensively for a variety of scenarios and tactics, with varied operator procedures and system configurations.

INITIAL STUDIES

Study Objective

The intent of the initial application of OICEA methodology was to determine if the technique yielded objective data of the type that might have led to system correction had such data been available during avionics design. The Sensor Station 3 (SS-3) crewstation onboard the P-3C ASW patrol aircraft was selected for study. Chronic operator overload problems were reported to exist at this station during certain missions. The operator overload was a consequence of requiring the operator to perform radar intercept and navigation information tasks while detecting, analyzing and identifying targets of military significance. The discussion below summarizes the OICEA study that was undertaken to investigate these problems. Further details are presented in Strieb et al (1978), Strieb and Harris (1978) and Strieb (1979).

Scenario

The SS-3 utilizes four non-acoustic sensors: radar, forward looking infra-red (FLIR), electronic support measures (ESM), and magnetic anomaly detection (MAD). Three of the sensorss (radar, FLIR and ESM) are used in the mission studied. The mission involved a surface search of an anchorage area off the coast of a potentially hostile nation. The operator's primary objective was to confirm the presence or absence of a specific ship within the anchorage area by acquiring ESM data from a target matching the signature of at least one of the emitters known to be on that ship, followed by visual confirmation and the acquisition of pictures of all contacts not positively identified as either neutral or friendly. The tactical constraints were:

(a) flight within a specified distance of the coastline was prohibited;

(b) total time in the anchorage area was to be minimized,

(c) a single direct overflight tactic was to be employed;

(d) the aircraft was to maintain a constant altitude and speed within the anchorage area,

(e) vessels not in the anchorage area were to be ignored after their location was determined.

Figure 1 shows the layout of the anchorage area with locations of targets and emitters. There were ten surface ships in the primary search area (the square area shown in Figure 1). Of these, six (including the primary target) were targets of interest. An additional twelve ships were located outside the primary search area. The ships (both inside and outside the area) had a total of 34 emitters and there were ten more emitters located on-shore. Emitters varied in duty cycle and in period of emission. The aircraft entered the area and flew from target to target, in turn, until all targets in the area of interest had been examined. The flight path minimized time in the area, within the constraints imposed by the primary mission objectives.

Configurations and Tactics

Three SS-3 configurations have been used in the fleet:

- Baseline -- The standard P-3C without FLIR.

- Baseline + FLIR -- The Baseline configuration with the addition of a FLIR sensor controlled by a joystick
- Update -- The P-3C Update II with an Infrared Detection System (IRDS), a FLIR system with an automated tracking capability.

Operator tasks and tactics vary as a function of the equipment available in each configuration. The specific tactics used for each configuration were developed with the assistance of, and were approved are by fleet SS-3 operators with recent experience in anchorage missions. In general, the operator tasks organized into five categories:

- Radar tasks -- requires plotting all targets and providing periodic navigation updates;
- ESM tasks -- requires evaluating and processing of emitter data as well as correlating bearing lines with radar contacts;
- FLIR -- requires FLIR tracking, image adjustments and recording;
- Mission Planning -- requires target selection and flight path control;
- Run-In -- requires performance of electronic intelligence (ELINT) gathering procedures, target type determination and mark-on-top procedures.

Results of Analysis

An anchorage mission is primarily an intelligence gathering exercise, where the information to be obtained includes ESM data and FLIR pictures, in addition to the basic requirement of identifying and locating targets in the anchorage area. Balanced against the objective of maximizing information was the requirement that minimum time be spent in the anchorage area. This leads to two classes of performance measures for the mission: the amount of information gathered, and the time to complete the mission. The information gathered is measured by the number of emitters correctly identified and, in those configurations with a FLIR system, the number of FLIR pictures obtained.

Performance -- Performance for each of the three system configurations is shown in Figure 2. The comparison of time and effectiveness for the three configurations is striking. When the maned FLIR was added to the Baseline, ESM effectiveness dropped from 100 percent to 82 percent, none of the possible FLIR pictures were actually acquired and time increased by 7 percent. Thus, the addition of FLIR not only failed to provide an enhanced capability as intended, but in fact interfered strongly with the ESM tasks. In the Update configuration, on the other hand, the automated FLIR maintained or improved performance on all measures, achieving 100 percent success in both ESM processing and FLIR acquisition, at a savings of 6 percent in time over the Baseline. Analysis of operator activity showed that the ineffective performance in the Baseline + FLIR configuration was due primarily to the characteristics of the FLIR system. The slew rate for the sensor was too slow for the operator to overcome lag time in response to aircraft movement. This problem could have been overcome by a straightforward control redesign had the deficiency been identified prior to fleet introduction. The capability to detect and diagnose problems at this level of detail from a simulated mission indicates a distinct strength of the OICEA approach.

Cost -- The OICEA cost analysis for the SS-3 simulation used only Operating and Support (O&S) costs, due in large to the difficulty of obtaining accurate data on research and development costs after a system becomes operational. The eight components of the O&S costs include: component rework, replenishment spares, other operating consumables, petroleum, oil and lubricants, standard depot level maintenance, engine rework, military personnel, and indirect operating costs. O&S costs proved to be satisfactory for this demonstration, although it tends to be relatively insensitive to configuration differences, since the major components are only slightly affected by changes in measures other than time.

Table 1 presents on-station flight time, estimated O&S costs per flight hour, and the on-station costs (total cost to perform the initial point to area departure). The most striking feature is the change in mission cost from Baseline to Update, a decrease of 5 percent accompanied by the sharp performance improvement already described.

Table 1. On-Station Cost and Data Summary

CONFIGURATION	ON-STATION FLIGHT TIME	O & S COSTS/HR	ON-STATION COST	EMITTERS IDENTIFIED	FLIR PICTURES
BASELINE	100%	100%	100%	100%	N/A
BASELINE & FLIR	107%	100%	107%	82%	0
UPDATE	94%	101%	95%	100%	100%

Relative Cost-Effectiveness -- Two factors discussed earlier were the relative nature of performance measures and the necessity for establishing a baseline of current cost-effectiveness against which proposed alternative solutions could be compared. One of the objectives of OICEA is to provide guidance to designers and decision makers about the most fruitful lines of development to solve a requirement for

increased system performance. One method of providing this guidance is the concept of "acceptance regions" demonstrated in Figure 3. This figure displays data from Figures 2 and 3 and Table 1 in a format which highlights the relative standings of the configurations examined. In order for a proposed solution to be considered, it should fall in or near the acceptance region. The size and location of this region will be governed by the cost-effectiveness of the current system and by other factors, such as the importance placed on cost as an evaluation factor. Cost could be of decreased weighting in the decision process if the threat was sufficiently critical.

Figure 3 deals only with performance on ESM processing. A similar figure could, of course, be constructed for FLIR performance. It should be noted that the use of On-station Cost is a convenient way of incorporating one performance measure (time) into the display of cost-effectiveness for another measure (ESM). The figure suggests one way of presenting cost/performance information. If research and development costs had been available, two or more comparable figures would be required.

Sensitivity Analyses

Several of the characteristics of the SS-3 simulation were modified in a separate series of sensitivity analyses (Strieb and Harris, 1978). These analyses (Table 2) sought to determine the stability of the initial simulation, to changes in operator characteristics and to changes in the tactical situation. For the latter change (Varied Approach), the aircraft's initial location was changed so that the aircraft entered the anchorage area from a different direction. For the former change (Slow Operator), a less responsive operator exhibiting information absorption and reaction times twice as long as those used in the standard simulation was modeled.

Table 2. Summary of Sensitivity Results

	MISSION TIME (% BASELINE)	OPERATOR FREE TIME (%)	EMITTERS IDENTIFIED (%)	FLIR PICTURES (%)
• BASELINE				
• STANDARD SIMULATION	100	20	100	—
• SLOW OPERATOR	104	0	100	—
• VARIED APPROACH	100	20	100	—
• BASELINE PLUS MANUAL FLIR				
• STANDARD SIMULATION	107 (140)*	7 (5)	82 (90)	0 (100)
• SLOW OPERATOR	118	0	41	0
• VARIED APPROACH	94	9	100	17
• UPDATE				
• STANDARD SIMULATION	94	26	100	100
• SLOW OPERATOR	106	2	100	100
• VARIED APPROACH	98	26	100	100

* PARENTHETICAL VALUES REPRESENT PERFORMANCE MEASURES OBTAINED WHEN MISSION OBJECTIVE WAS TO OBTAIN FLIR PICTURES OF ALL TARGETS OF INTEREST

Operator Free Time -- The measure of free time in Table 2 is defined as the amount of time during each simulation in which the operator was performing monitoring functions or routine FLIR tracking and there were no unprocessed contacts to be entered. Thus, "free time" does not imply that the operator is not performing any actions, but rather that the activities involved are the minimum required to maintain the system in its desired state.

The statistics in Table 2 for operator free time show that the Update configuration provides the operator with more free time than either of the other two configurations. The statistic is relatively insensitive to the initial location of the aircraft in all configurations but shows a marked decrease for the slow operator. In all configurations, the slow operator either is, or borders on, being overloaded. This indicates the need to insure that actual operators meet the proficiency criteria implied by the HOS definition of a "trained operator."

ESM Utilization -- The ESM processing results in Table 2 can be summarized as follows: In both the Baseline and Update configurations, the operator is capable of keeping pace with the task. Even in two of the three Baseline plus FLIR categories, he can keep pace -- but just barely. This is because there are sufficiently large distances between targets to enable him to catch up and because the operator was able to divide his attention between the FLIR tracking and ESM processing tasks. Whether an actual operator has the ability to divide his attention as efficiently as HOS predicts is uncertain. What is clear is that once the FLIR tracking procedures are initiated, the operator is extremely busy and can fall behind in the ESM processing quite easily.

FLIR Utilization -- There is a problem in determining the percentage of FLIR pictures obtained. Although the operator might not get through the entire sequence of adjusting the gain, contrast, brightness, focus and polarity, the pictures that are obtained without these adjustments may still be usable. Therefore, when computing the percentages shown in Table 2, it was assumed that if the target was on the screen at the time the FLIR run-in procedures werre initiated, then the target was able to be successfully photographed. Even by this generous criterion, operators in the Baseline + FLIR configuration were

still clearly incapable of attaining a satisfactory level of performance. The primary reason for this was that the slew rate for the manual sensor was too slow for the operator to be able to satisfactorily track the targets at the required ranges.

The SS-3 operator's performance might have improved had the pilot been told to wait until the operator had completed the picture-taking operations before proceeding to the next target. To examine this possibility the tactical constraint that demanded that the aircraft spend minimum time in the anchorage area was removed. Aircraft flight dynamics were modified so that the aircraft would circle each target, until the operator had sufficient time to obtain a satisfactory picture (Strieb,1979). Implementation of these changes yielded the set of values shown in parentheses in Table 2. As expected, the number of FLIR pictures acquired increased to 100 percent at the cost of significantly increasing mission time in the anchorage area. The operator free time was diminished slightly and an 8 percent increase in identified emitters was obtained.

Utilities and Their Variations

Simulation of the anchorage mission produced three measures of system effectiveness -- time, percent emitters identified (%EI), and percent FLIR pictures obtained (%FP). These measures, particularly the latter two, are mission-specific and partly dependent on the specific tactical environment. In the analysis, they have been treated as separate indices of performance. It would be more desirable when evaluating cost/performance to deal with a single global measure of performance which aggregates all possible measures of success. To do this, it would be necessary to specify value of each measure in the total context of satisfying mission requirements. These values are the utilities associated with each performance measure. Weighting performance measures by their utilities can yield the desired global measure.

Obtaining utilities is not simple. While a properly defined mission requirement should identify what performance is demanded and what the associated utilities are as an integral part of the requirements statement, such data are generally not provided. It may be possible in specific cases to obtain utility judgments from policy makers, but this is not a common practice at present.

Another way to examine the effect of utility weighting is to compute crossover points for each acceptance region. This is done by systematically varying utilities through their probable ranges and examining the changes to the system alternatives relative to the acceptance regions. Although data from this study is not particularly suited to such manipulation due to the clearcut superiority of one version, examples to illustrate application of this concept can be given for the three configurations.

An empirical expression can be written in the following form to combine the three measures of system performance:

$$\text{Cost Performance Index} = \frac{(100-{}^{U}FP)\ (\%EI) + {}^{U}FP\ (\%FP)}{\text{On-Station Cost}}$$

where, ${}^{U}FP$ is the utility weight selected to designate the value of FLIR pictures.

Figure 4 shows the effect of varying ${}^{U}FP$. If the objective is to minimize On-Station Cost relative to total performance, there is no combination of utility weights which will result in Update being judged less effective. The Update configuration is superior regardless of the "true" utility. In addition, no values of ${}^{U}FP$ exist for which performance with the added manual FLIR sensor exceeds the Baseline configuration. However, by changing the mission objectives and constraints to give priority to obtaining all FLIR pictures, the cost performance index can be raised so that the Baseline + FLIR configuration exceeds the Baseline (Manual FLIR Revised) although it is still significantly less than Update. It should be noted, moreover that the "risk" involved in the Manual FLIR Revised configuration is dramatically higher than that for other simulations. Staying on station to obtain all the FLIR pictures increases time in the anchorage area by 40 percent over Baseline. If a hostile condition exists, this increase could well be unacceptable. The concept of risk as a mission performance measure has not been explicitly considered in these studies. but is implicit in the initial tactical constraints. Risk is another measure that could be quantified, assigned a utility value, and considered in tradeoff curves similar to those in Figure 4.

The particular configurations and parameters used in the SS-3 simulations lead to relatively straightforward conclusions about configuration value regardless of utilities. It is easy to conceive of situations in which decisions would not be so clearcut. The concept of determining boundaries for which decisions on relative cost-effectiveness would be unchanged is applicable to virtually any multiple performance measure problem.

CURRENT APPLICATION

Objective

The SS-3 simulations just described used an operational weapons system to illustrate the potential value of the OICEA approach for evaluating the cost-effectiveness of alternative avionics configurations.

An effort is currently underway that will apply the OICEA methodology to an advanced avionics system still under development. The objective of the current effort is to develop a simulation capability that will be available by the time the system is initially deployed so that modifications to the avionics, proposed as a result of operational experience, can be evaluated for their relative cost-effectiveness and impact on other mission functions. The system selected for this OICEA application is an advanced acoustic signal processor being developed for the U.S. Navy's P-3C ASW patrol aircraft. The application focuses on the acoustic sensor station operators (SS-1 and SS-2) on this platform. It is presented here principally to illustrate the flexibility of OICEA to accommodate extremely sophisticated systems and to describe the organized sequence of steps required to use the technique.

A two phase effort is planned. The first phase will consist of three simulations with varying combinations of current and advanced signal processors and sensors:

(1) A simulation in which the operator uses the <u>current</u> signal processor and <u>current</u> sensor systems and

(2) A simulation in which the operator uses the <u>new</u> signal processor with <u>current</u> accoustic sensors

(3) A third simulation using the new processor and <u>new</u> sensors.

In the second phase of the study, the simulations will be modified in accordance with proposed avionics modifications to determine the cost-effectiveness of these modifications prior to implementation.

<u>Scenario</u>

The mission to be simulated in this demonstration is an open ocean convoy screening mission. The aircrew on the P-3C has been tasked with providing protection for a convoy consisting of twenty ships. Each P-3C can remain on-station for approximately six hours, during which time the aircrew deploys passive acoustic sensors in wedge-shaped patterns ahead of the intended course of the convoy. Each wedge contains nine sensors. At the time the simulation begins, the sixteenth sensor has just been deployed (Figure 5). Two hostile targets with differing threat characteristics are on intercept courses with the convoy and are about to penetrate the outermost wedge. Once the sensor station operator has obtained contact on either of the targets, the tactical coordinator (TACCO) may instruct the pilot to fly to the sensor maintaining contact in order to deploy additional sensors around the contact. As additional contact information is obtained and the location and classification of the target becomes more certain, the TACCO will deploy active sensors to obtain precise fixing information.

The localization problem is complicated by the enemy's evasive capabilities -- course and speed changes at random intervals, as well as periodic depth changes that alter the enemy positions relative to the ocean's thermal layer. Moreover, if the aircrew deploys active sensors, the targets can take additional evasive maneuvers, dependent on their locations relative to the locations of the active sensors.

<u>Sensor Station Operator's Tasks</u>

The sensor station operators (SS-1/2) monitor the sensors as they are deployed and report any contacts obtained to the TACCO. Using the advanced signal processor, the operators can monitor many more sensors than with current signal processors, but can not continuously monitor all the sensors that will be deployed during the course of the mission. Therefore, the operators (and the TACCO) must decide which sensors to monitor, when to monitor each and what modes (omnidirectional or directional, active or passive) to use for each sensor, based upon the characteristics of the mission at any particular time.

Data is displayed to the operator as frequency spectra ("grams"). The operator can configure the system so that it will automatically alert him if certain patterns of lines appear on the grams indicating specific types of hostile targets. Alternatively, the operator can depend on his own ability to recognize the target characteristics directly from the gram data. The system has a wide variety of electronically implemented aids to assist the operator in reading and interpreting the gram data. These and a host of other functions are callable from a keyboard that consists of approximately 100 momentary switches and 20 projection readout switches providing over 190 different system functions. Thus a major responsibility of the sensor station operator is to decide how best to take advantage of the system's capabilities. These activities and decision processes are described by the procedures developed as inputs to the OICEA/HOS model.

<u>Current Status and Future Use</u>

At the present time, the baseline SS-1/2 simulation is being developed. Even at this early stage, some benefits are apparent from the OICEA methodology (beyond the expected benefits for cost-effectiveness evaluation). First, the analysis has provided detailed procedural definitions that describe how the operator will use the system and the decisions that must be made. While such procedures and decision points should be a natural part of the system development process, they are often not developed until late in the development cycle. Standard reference sources describe how individual system components are used, but not how the operator integrates the use of these component functions to perform his job. OICEA requires the explicit definition of the specific decision rules that an acoustic operator uses to decide what actions to take in specific situations. For the current simulation, a catalog of more than one hundred key decision points has been developed. Such a catalog has several possible uses. First, it provides the data needed to train operators to optimally utilize the system. By modifying the procedures, one can examine the effects of alternative sensor monitoring disciplines. It provides a means of testing alternative tactical strategies that previously were testable only in hardware-based

simulators or through real-world exercises. It enables the criteria used by operators to identify, localize and classify targets to be examined in detail. It provides a method by which operator decisions, decision situations, and decision processes can be identified -- a capability which will be increasingly important as it becomes more feasible to incorporate decision-aiding algorithms into operational avionics systems. Thus OICEA can help to pinpoint where decision-aiding systems would be most valuable; it can indicate what the parameters of the decision situation are and how they interact; and it can be used to evaluate what performance improvements one could expect from the use of specific decision aids.

The Role and Value of Models

The current SS-1/2 simulations are designed to illustrate the important role which can be played by system cost-effectiveness modeling in the total cycle of system development, modification and update. Complete system models must be developed concurrently with the system itself, maintained and kept current as the system evolves to operational deployment and beyond. Although dynamic hardware simulators of systems will normally be available for use in evaluation toward the end of the development cycle, these are extremely expensive to build and modify and are not always kept in a ready status after the system has been deployed for a number of years. The evaluation of modifications to operational systems can frequently not be performed on an up-to-date mission simulator without extensive investment and time delay. It is thus critical that computer models of systems be ready prior to operational deployment and regularly modified to provide immediate availability when a proposed system update must be evaluated.

CONCLUSIONS AND IMPLICATIONS

The work described in this paper was initiated in response to the observation that avionics modifications and updates, introduced to improve total system performance, frequently had little effect or even adverse impact on that performance. The SS-3 FLIR problem serves as a classic example of such a problem. The objective of the initial study was to determine if the OICEA approach would predict such performance decrements and uneconomical configurations. This objective was clearly achieved, although substantial development is still required, particularly in the costing area.

These conclusions and the accuracy of the simulations themselves were substantiated by fleet reports on problems experienced by SS-3 operators, who have great difficulty in performing manual FLIR tracking and ESM processing simultaneously. Standard practice was for another operator to use a folding chair at the SS-3 console to assist during key mission phases. This difficulty and its root causes were readily identified by the simulation. Had the OICEA technique been available and properly utilized for evaluating alternate FLIR systems, a system would have been identified that would have accomplished the desired results and the development and deployment of an unacceptable configuration could have been prevented.

Computer modeling of baseline systems followed by modeling of proposed changes is highly effective as an initial step in system modification and is a rapid and low cost technique compared to hardware approaches. It is critical in using this approach that a computer model with both a realistic avionics and an operator component be available at or before fleet deployment of the system. The acoustic sensor operator simulations currently under development are an attempt to satisfy that requirement for the P-3C Update III, a system with highly complex avionics. Whether or not the model can achieve satisfactory simulation must still be determined. If the effort is successful, the potential for savings in development and deployment costs and for improvements in system performance is enormous.

A second encouraging finding concerns the ease with which the HOS procedural language can be used to systematically vary mission and equipment parameters and operator characteristics and decision processes. Such parameter manipulation allows the determination of the robustness of the simulation outputs to idiosyncrasies of particular parameter combinations, and provides identification of specific equipment or procedure characteristics which render the configuration ineffective. For the SS-3, relatively minor changes in design of the FLIR control and relocation of some displays would likely have improved performance sufficiently for the manual configuration to serve as an acceptable interim alternative to the automated system. The OICEA approach would have allowed the identification and evaluation of these changes at very low cost.

The rationale for OICEA is to determine whether specific cost and performance questions which should be raised about all avionics modifications in manned systems could be answered through the use of computer models with a realistic human operator component. Our results, at least for the mission and configurations considered in these studies, clearly support this approach to system design.

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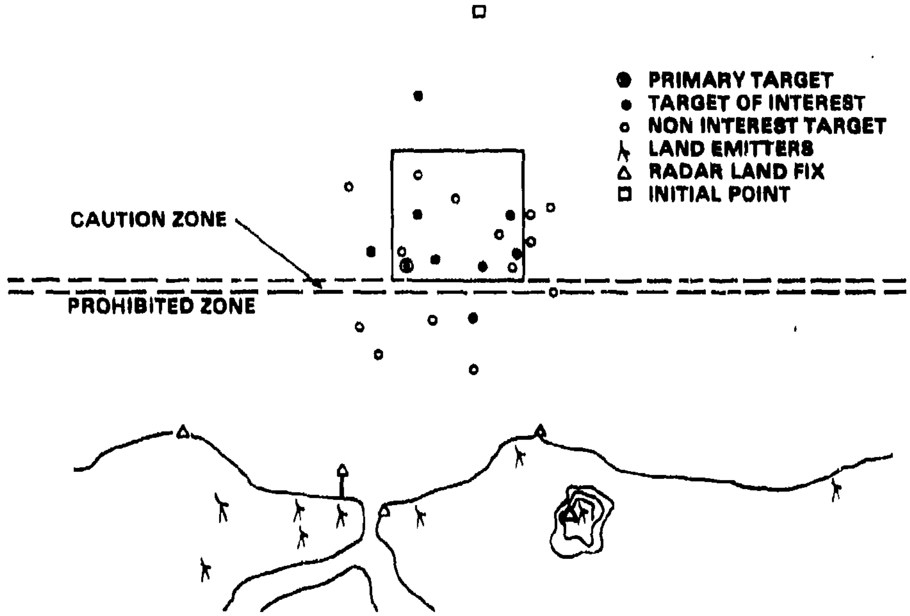

Fig.1 Layout of anchorage area

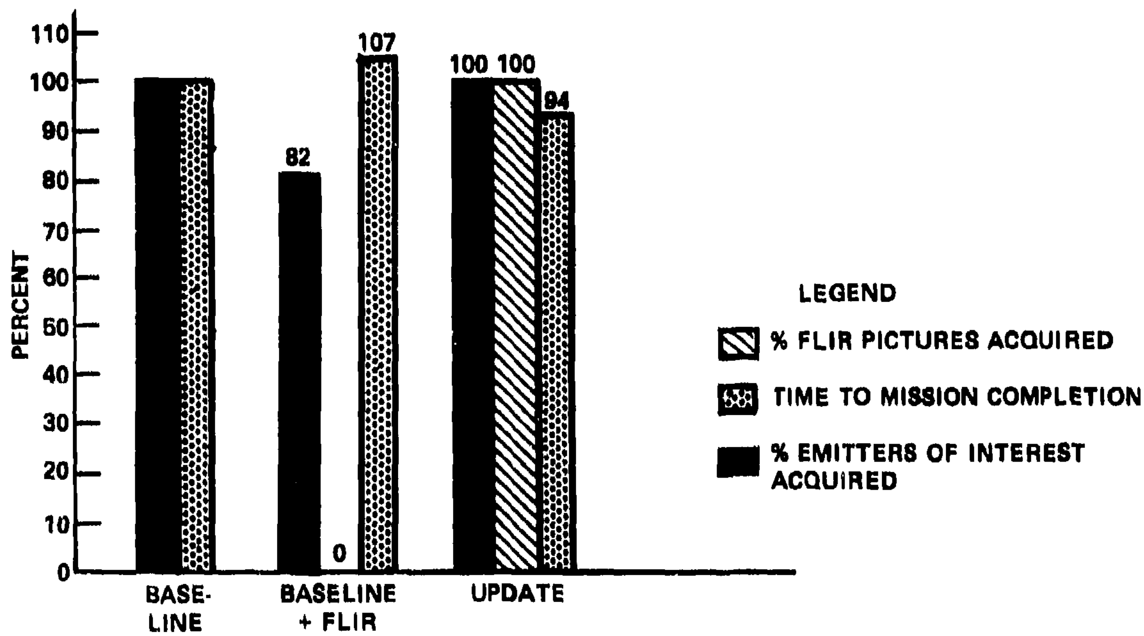

Fig.2 Summary of system performance

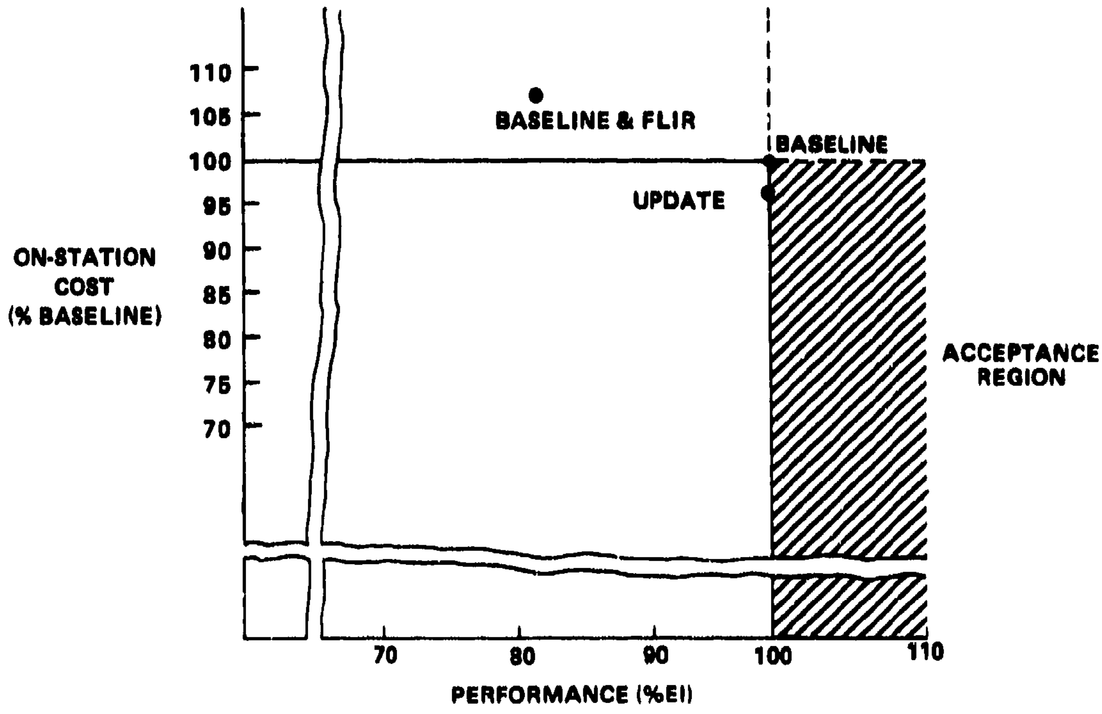

Fig.3 Relative cost effectiveness analysis

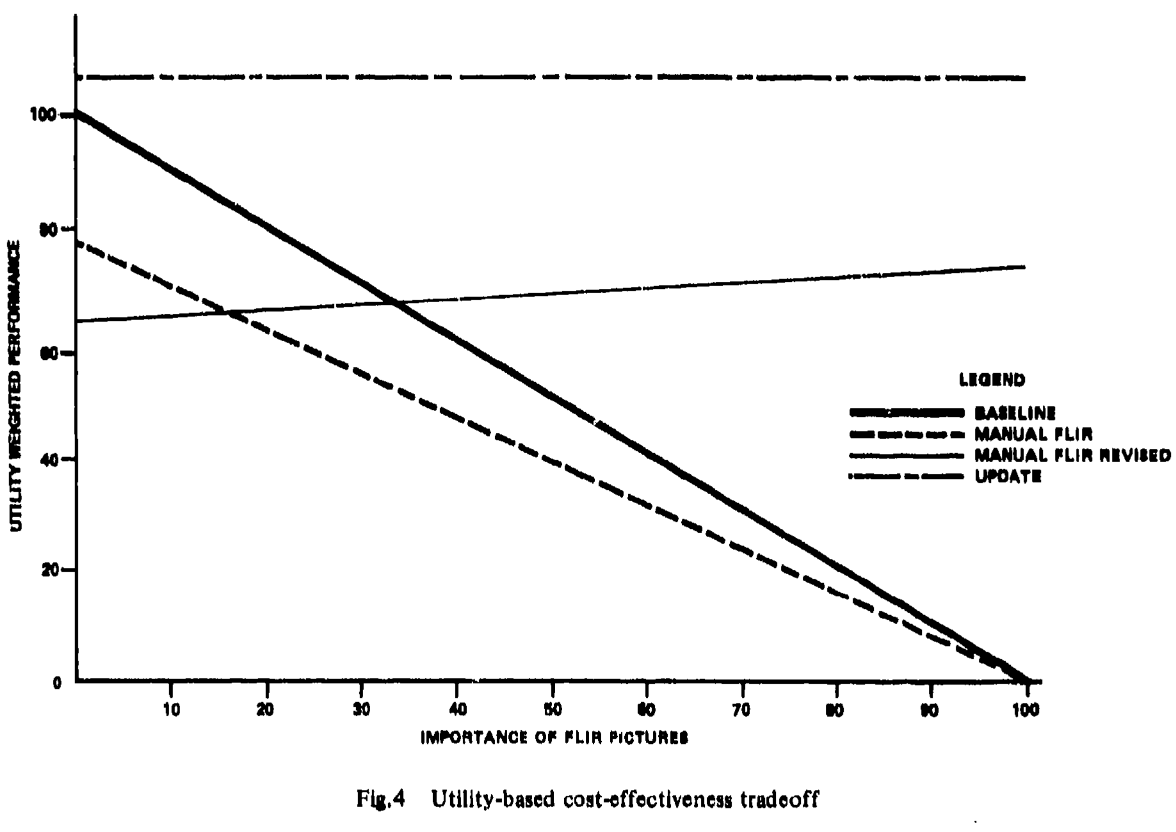

Fig.4 Utility-based cost-effectiveness tradeoff

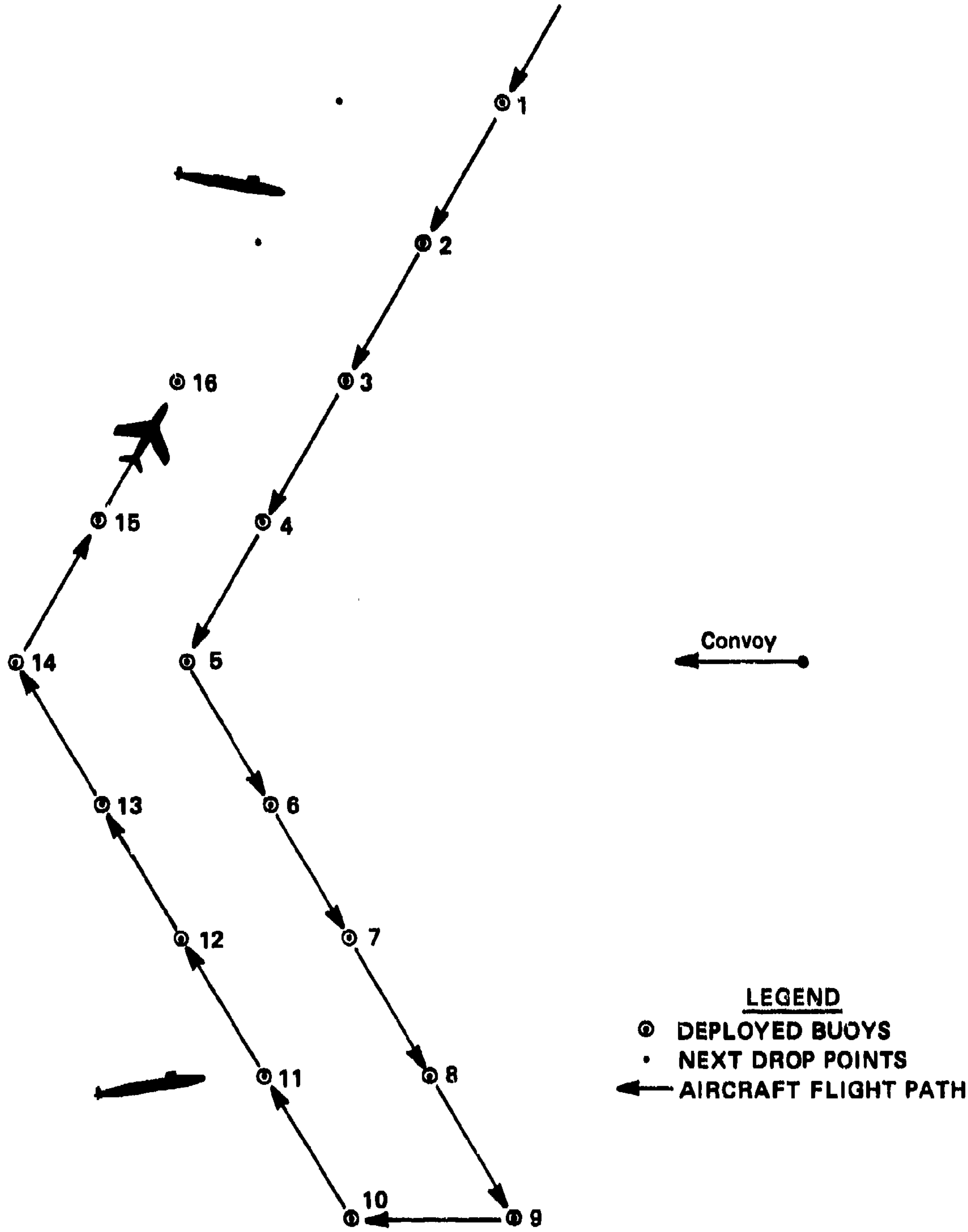

Fig.5 Initial situation

PREDICTING FIELD OF VIEW REQUIREMENTS FOR VSTOL AIRCRAFT APPROACH AND LANDING

BY

PAUL M. LINTON
U. S. NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PENNSYLVANIA
AND

WARREN F. CLEMENT
SYSTEMS TECHNOLOGY INCORPORATED
MOUNTAIN VIEW, CALIFORNIA

SUMMARY

The most difficult piloting tasks encountered in vertical/short take-off and landing (VSTOL) aircraft are the transition from aerodynamically supported flight to thrust supported flight, and the subsequent recovery aboard a ship or unprepared forward site. A significant portion of the difficulty experienced in these piloting tasks is due to the fact that out-of-the cockpit visibility in past and current VSTOL designs has generally been too restricted to provide adequate visual cues. Aircraft designers have had difficulty in treating field of view problems since neither clear criteria nor standard procedures exist for determining required outside visibility for this class of aircraft.

In response to this deficiency, this paper develops a rationale for quantitatively determining fixed-wing VSTOL field of view requirements. It provides a relevant predictive and evaluative tool which models the complex interaction between human visual processes, the vehicle approach profile, and the operator flight path control performance. The model is intended to complement and support avionic system and crewstation design models. Applied to the development of a new air weapons system, this technique significantly affects avionic and airframe design. The model specifies precise visual requirements for recovery aboard defined shipboard pads or forward sites. Those visual requirements which cannot be satisfied by pilot tasking or canopy/window considerations must be fulfilled by innovative avionics and display concepts.

INTRODUCTION

The most difficult piloting tasks encountered in vertical/short take-off and landing (VSTOL) aircraft are the transition from aerodynamically supported flight to thrust supported flight, and the subsequent recovery aboard a small ship or unprepared forward site. A significant portion of the difficulty experienced in these piloting tasks is due to the fact that out-of-the cockpit visibility in past and current VSTOL designs has generally been too restricted to provide adequate visual cues. Aircraft designers have had difficulty in treating field of view problems since neither clear criteria nor standard procedures exist for determining required outside visibility for this class of aircraft. The simple solution of raising the pilot's seating position creates immediate problems with control reach and actuation. The proper solution requires consideration of pilot visual requirements, airframe/canopy design, avionics design, and crew station design.

OBJECTIVE

The objective of this study was to develop the rationale and methodology for quantitatively determining fixed wing VSTOL field of view requirements. There have been some rudimentary efforts in the past addressing this issue, but most of the attempts have considered only aim point visibility relative to the approach path angle and vehicle pitch attitude. That is, the efforts were usually simplistic geometric exercises. Generally missing from these models was an appreciation of the interrelationships among such parameters as nominal approach profile, pilot's flight control precision in the face of environmental disturbances, visibility, and guidance and control cues (such as visual landing aids) afforded by the landing site.

The present study, on the other hand, combines the dynamic modeling of (a) the recovery guidance and control situation, (b) the disturbance environment, (c) the augmented aircraft, (d) the pilot's multiloop control activities, (e) the perceptual behavior of the pilot, and (f) the resulting geometric properties of information elements within the visual field. These factors are combined through the use of closed-loop pilot-vehicle analysis employing validated models of human pilot behavior.

Using this technique, the analyst is able to establish the essential information elements in advance of simulation and to establish those visual cues which provide the pilot with the best sensitivity to vehicle motions during the recovery. The analyst can then use the results of this method, in combination with mission, vehicle, shipboard and environmental constraints to suggest optimum aircraft field of view requirements.

PROCEDURE

The methodology developed by this study can be conceptually partitioned into four clearly defined steps. In the interests of brevity, the four steps can be discussed in outline form only. As always, the quality of any final product can be no better than the quality of its composite supporting framework. The analytic efforts comprising the framework in this study are quite rigorous. The numerous references provide sufficient detail for the serious reader interested in specific assumptions and analytic techniques employed within each step.

I. Kinematic Representation of Aircraft Approach Trajectories

The first step in the procedure is to select and define intended approach trajectory(ies) of the aircraft with respect to the recovery area on a moving ship or shore based site. This requires determination of the sequence of nominal operating points (range, bearing, and altitude with respect to the terminal hovering point over the pad) as a function of time. The analyst may also specify ship velocity, if appropriate, desired type of approach trajectory, deceleration and terminal hovering coordinates.

II. Pilot/Vehicle Performance

The next step requires exercising an analytic model of the pilot-vehicle combination executing the intended approach trajectory under the influence of turbulence, ship motion, degraded visibility, and pilot variability. The results of this step are mathematical relationships among trajectory variables, ship motions, turbulence, and piloting noise on one hand and the resulting angular and translational kinematics of the aircraft on the other.

III. Visual Element Motion Analysis

Having established one or more VSTOL approach geometries to the landing pad (Step I), and having defined the performance of the pilot-vehicle combination during the critical transition and hovering phases (Step II), it is necessary to interpret the pilot's perceptions of the external visual cues upon which he relies. For the purposes of this study, the representative visual cues selected were most elementary; the deck pad and hangar delineation for a small Naval destroyer (DD 963 class). The ship class selected has a nominal 40 ft. by 60 ft. recovery area and a 40 ft. wide by 20 ft. high hangar face. The analyses conducted in this study were directed toward determining the required viewing angles to maintain visual contact with these shipboard elements. Certainly other recovery aids or landing area geometry could be examined and numerous options are available in Ref. 1.

IV. Field of View Requirements

Combining the nominal angular motions and positions of the visual cue referrents from Step III with the previously determined estimates of variability (due to disturbances) allows the analyst to define explicitly the location of essential visual cues for guidance and control of the aircraft within the pilot's forward visual hemisphere. Field of view requirements can be established utilizing this information in combination with related information concerning canopy design, airframe obstructions, and optical or electro-mechanical landing displays.

TECHNIQUE APPLICATION

Five representative decelerating trajectories were examined during the development of the methodology. Included in the sample were:

- A homing or pursuit trajectory in which the aircraft flight path vector is always pointed toward the ship.
- A collision trajectory which follows a straight line path in the earth reference frame toward a predetermined intercept point with the ship.

- A trajectory which maintains a constant bearing with respect to the ship (such as a conventional approach using fixed line up and glide slope angles).
- A constant sink rate trajectory (at constant horizontal bearing) where deceleration along the earth X-axis is constant.
- A constant altitude trajectory (at constant horizontal bearing) where deceleration along the earth X-axis is constant.

Figure 1 depicts graphically the five vertical plane trajectories and three horizontal plane trajectories in the ship's frame of reference. There are only three trajectories present in the horizontal plane since the constant sink rate and constant altitude trajectories coincide with the constant bearing trajectory in the horizontal. The ship is underway at 20 kt on a fixed course in calm air. Thus the forward motion of the ship is generating the relative wind-over-deck (WOD) of 20 kt along the ship's centerline. (Subsequently we shall estimate the disturbing effects of the ship's motion and air wake turbulence in sea state 5 with 43 kt WOD.) Each trajectory terminates at 40 ft deck height directly over the center of the recovery circle. The termination of the homing trajectory is aligned with the WOD and coincides with the constant altitude trajectory by design without special maneuvers, but the missed approach route is blocked by the aft mast and stack. Both the straight line (in the earth reference frame) and the constant sink rate trajectories require special terminal maneuvers to arrest the descent and to match the ship's velocity. The constant bearing trajectory (in the ship's reference frame) is compatible with existing visual landing aids on the ship. Maneuvering requirements for the homing and constant bearing trajectories are discussed in Ref. 2.

As previously stated, Step I of the methodology requires the time dependent determination of the sequence of operating points (range, bearing, and altitude) with respect to the terminal hovering point. The details of the closed loop analyses conducted to determine the trajectories are beyond the scope of this paper but are clearly presented in Ref. 3. Tables 1 and 2, however, present a qualitative summary of the relative advantages and disadvantages of the selected trajectories. Although it was not an objective of this study to select a best or most desirable trajectory, it is readily apparent from Tables 1 and 2 that certain trajectories possess more advantages than others. The field of view requirements necessary to maintain visual contact with the deck pad and hangar face (from 700 ft. range to the hover point), however, have been computed for all approach trajectories.

TABLE 1

TRAJECTORY COMPARISONS - HORIZONTAL PLANE

CONSIDERATION	HOMING	CONSTANT BEARING (INERTIAL AXES)	CONSTANT BEARING (SHIP AXES)	STRAIGHT PATH
Ship-to-aircraft surveillance	Large changes in bearing angles	Small changes in bearing angle unless ship turns	Constant bearing angle	Large changes in bearing angle
Aircraft-to-ship visibility	Good, aircraft always pointed at ship	Fair, moderate change in bearing angle, may require wing-low for visibility	Fair, moderate change in bearing angle, may require wing-low for visibility	Poor, large variation in bearing angle, may require wing-low for visibility
Landing pad perspective	Modest changes	Small change unless ship maneuvers	No change	Larger changes than homing trajectory
Aircraft maneuvering	Moderate lateral g at short range	Low lateral g	Low lateral g unless ship turns	None until terminal maneuver unless ship maneuvers
Bolter and obstacle avoidance	Fair, on collision course from astern	Good, approach from side, on collision course only if stop decelerating	Good approach from side, on collision course only if stop decelerating	Fair, approach from side, on collision course if maintain deceleration schedule (unless bias aim point)

TABLE 2

TRAJECTORY COMPARISONS - HORIZONTAL PLANE

CONSIDERATION	HOMING	CONSTANT BEARING (INERTIAL AXES)	CONSTANT BEARING (SHIP AXES)	STRAIGHT PATH
Guidance data requirements	LOS relative to aircraft heading	Angular velocity of LOS	Deviation from ship-fixed beam	Ship and aircraft positions (inertial axes)
Guidance hardware	Aircraft can track passive ship	Aircraft can track passive ship but need to derive angular rate of LOS	Ship transmits reference beam; or tracks aircraft and transmits commands/data	Aircraft can track passive ship but need higher precision for ship prediction
Compatibility with VLA's	Good at short range; always approach from astern	Fair, approach angle varies slightly if ship does not turn, can vary greatly if ship turns	Excellent, approach angle is constant	Fair, requires modest turn on to VLA unless ship maneuvers
Effects of ship maneuvering	Slight	Slight	Slight for speed changes. Large for turns; may be impossible to follow at long range	Modest aircraft maneuvering required but complicates ship prediction

Once the approach trajectories have been mathematically represented, we may move on to consideration of the pilot's view from each nominal trajectory in the absence of aircraft perturbations. The perspective view of the recovery deck of a DD-963 class destroyer is depicted for each of the five trajectories in Figures 2 through 6. The perspective views begin with the minimum assumed visual detection range of 700 ft and end with the pilot's eye 40 ft above the center of the recovery circle. The illustrations assume that the pilot is looking at the center of the recovery circle, which appears elliptical in perspective; the figures omit, for the time being, the obscuring effect of any cockpit structure. The origin of the horizontal viewing angle (λ) axis corresponds to the horizontal reference line of sight relative to the nose of the aircraft at each value of slant range, R_m; thus the centers of the landing pads appear to be in the same horizontal line of sight for the homing and constant bearing trajectories, but not for the straight line trajectory. The origin of the vertical viewing angle (μ) axis corresponds to the vertical line of sight; thus the centers of the landing pads reflect the depressed elevation angles (LOS_v) relative to the horizon at each slant range, R_m.

As long as the aircraft (pitch and roll) attitude is approximately level, field of view requirements for the nominal unperturbed approach trajectories may be interpreted directly in terms of the angles λ and $\mu + LOS_v$ for all trajectories except the straight line (in inertial space), for which the horizontal field of view requirement must be interpreted in terms of $\lambda + \Delta\psi$.

Figures 7 and 8 are projections of the landing pad and hangar face, respectively, when the aircraft has reached the hover point 40 ft over the center of the pad ($R_m = 0$). In Figure 7, the pilot is assumed to be looking at the center of the recovery circle which is, of course, at the nadir, but in Figure 8, his line of sight (LOS) is shifted to the upper center of the hangar face. Even that line of sight is depressed over 33 deg from the horizontal plane.

Having examined pictorially and graphically the undisturbed case, the more realistic case which takes into account aircraft perturbations resulting from environmental and pilot control factors may be considered. It is readily apparent from previous figures that field of view requirements will be greatest near the ship in hovering and near-hovering flight. Therefore, Figures 9 and 10 illustrate the combined effects of rotational and translational disturbances in the controlled aircraft motion on these hovering and near-hovering field of view requirements. The details of the extensive analyses required to provide the present examples are documented in Refs. 4 and 5 and will not be repeated here. The results depend in a critical way on the selected model of the ship's airwake disturbance environment. The two examples of perturbed field of view requirements include: (1) from 50 ft range-to-go (to the hovering point)

on a constant relative bearing trajectory and (2) from the hovering point itself 40 ft above the center of the deck. For selected points of regard by the pilot, we can estimate Gaussian statistical variances in the required field of view caused by the predicted variances in the six aircraft degrees of freedom listed in Table 3. Corres-

TABLE 3

SUMMARY OF ILLUSTRATIVE MOTION ERROR VARIANCES
FOR USE IN EXAMINING HOVERING FIELD OF VIEW REQUIREMENTS

Sea State 5

Wind-Over-Deck = 43 kt

Ship Speed, V_s = 20 kt

Clockwise Wave Direction Relative to Ship's Stern, μ = 120 deg

Mean-Squared Ship Motions at the Center of the Landing Pad (Relative to Inertial Space) for the DD963		Mean-Square Aircraft Motion Relative to Ship while Station-keeping under Manual Control	
Ship Motion	Variance	Aircraft Motion	Variance
Roll σ_ϕ^2	$(2.02\ \text{deg})^2$	Roll σ_ϕ^2	$(2.5\ \text{deg})^2$
Pitch σ_θ^2	$(0.77\ \text{deg})^2$	Pitch σ_θ^2	$(3.0\ \text{deg})^2$
Yaw σ_ψ^2	$(0.30\ \text{deg})^2$	Yaw σ_ψ^2	$(2.1\ \text{deg})^2$
Surge σ_x^2	$(0.40\ \text{ft})^2$	Surge σ_x^2	$(11.6\ \text{ft})^2$
Sway σ_y^2	$(2.05\ \text{ft})^2$	Sway σ_y^2	$(15.5\ \text{ft})^2$
Heave σ_z^2	$(2.71\ \text{ft})^2$	Heave σ_z^2	$(19.5\ \text{ft})^2$

ponding distributions of perturbations in terms of viewing angles will, however, tend to be increasingly skewed as the point of regard departs from the nominal line of sight (the optical axis of the picture plane), because of the tangent relationship between picture plane coordinates and viewing angles. Nevertheless, we can approximate the root-sum-squared angular variance for the pilot's nominal line of sight to the center of the recovery circle by the large ellipse in Figure 9 at 50 ft range-to-go to station-keeping. The root-sum-squared variance for the pilot's nominal line of sight to the upper center of the hangar face is shown by the large ellipse in Figure 10 while the pilot is attempting to keep on station over the deck. These extreme estimates of variability confirm the desirability, from the standpoint of reducing field of view requirements, of providing visual cues and visual aids above the hangar for assisting the pilot in arresting and approach and providing hovering guidance.

These extreme estimates of variability also emphasize the need for high authority, high bandwidth flight control systems in order to function effectively in this environment -- much higher than is typical of current helicopter practice. The allowable aircraft motions due to all causes are only a few feet -- Ref. 6 states "3 to 4 ft" in "allowable" touchdown error. If we interpret "allowable" as 2σ, Table 3 shows that the square root of the sum of the x- and y-variances in deck motion alone at the center of the pad slightly exceeds this "allowable" touchdown error. Without chasing the deck, this allowable touchdown error thus represents the best precision one might expect from a guidance and control system which regulates so well that no errors are contributed by aerodynamic disturbances or the pilot's divided attention. Graphic representation from the pilot's station-keeping perspective of this apparent σ-variation in the center of the pad due to ship motion alone is shown by the smallest central σ-ellipse at 50 ft range-to-go in Figure 9 and at zero range-to-go in Figure 10.

With this assessment of the variability in the viewing angles required of the pilot with respect to his cockpit reference, we conclude our analyses of field of view requirements in the extremely severe disturbance environment to be expected in sea state 5 with 43 kt wind-over-deck. The predicted field of view requirements with manual control appear to be so great that more confidence is needed in the validity of the predicted airwake disturbance environment on which this analysis is predicated before these expectations can be converted into design requirements for field of view, which are, in turn, based on high authority, high bandwidth flight control systems.

DISCUSSIONS

It would be presumptuous for the authors to infer that the resultant methodology can, by itself, produce discrete values which precisely define the field of view requirements for the VSTOL pilot. The present technique is definitive in determining field of view requirements when visual contact must be maintained with any predefined point on the ship or land based site. It bears emphasizing, however, that field of view requirements, per se, depend upon numerous factors including but certainly not limited to:

- approach trajectory
- perceptual cues available to the pilot
- vehicle handling qualities
- vehicle airframe/canopy/crewstation characteristics
- display system capabilities
- environmental characteristics
- shipboard or aircraft visual landing aids

While the present methodology takes into account more of the above factors than previous work conducted in this area, it is most beneficially used in conjunction with other engineering factors in deciding upon field of view requirements.

Consider, for example, a hypothetical case where for either operational or policy constraints a constant sink rate trajectory at constant bearing must be utilized. Using the methodology developed in this paper, it can be determined that the pilot will require almost 68° over-the-nose visibility to maintain visual contact with the center of the landing pad when he is located 50 ft from the hover point, and that figure assumes the absence of any environmental disturbances. In a situation such as this, the field of view methodology does not truly provide requirements but serves as a design tool in that it alerts engineers to the need for possibly greatly sophisticated displays or an automatic landing system. If these solutions are impractical or unfeasible then perhaps operations and systems analysts can reexamine the need for a constant sink rate trajectory. In this respect, it is apparent that this methodology can rightfully be considered a design tool. It can be extremely useful when input parameters to the models such as approach parameters or environmental disturbances are varied systematically while the model is exercised repeatedly.

This methodology for determining field of view also has secondary implications for design engineers working in the areas of head up displays (HUD), conventional instrumentation, automatic guidance and landing systems, in addition to human operator modelers. HUD designers, for example, must be aware of where the pilot is looking for visual cues in order to avoid cluttering those regions with excess symbology. Additionally, the HUD designer must consider the possible field of view benefits of a wide angle head up display traded off against wide angle displays technical problems.

Conventional crewstation design engineers must be concerned with field of view implications in that one of the most obvious methods of increasing over the nose visibility in any aircraft is reducing the height of the instrument panel and glare shield. If this became a viable alternative, then crewstation designers may be forced to wrestle with such issues as removal of the control column, elimination or miniaturization of instruments or possibly a "swing away" instrument panel. It goes without saying, of course, that if these more exotic alternatives cannot be accommodated then the crewstation designer must direct his energies to radically improved display design. Conventional instrument panel or horizontal displays may prove adequate if the information integration, format, accuracy, and sensitivity are superior to that presently available.

The relationship between automatic guidance and landing and field of view requirements is a subtle one but nevertheless valid. All automatic guidance and landing systems must have a manual override to enable the pilot to take control if and when he deems necessary. Regardless of the technical complexity and capability of the system it will not be effectively utilized if the pilot has little confidence in it. Undoubtedly, the pilot will be closely monitoring the outside visual scene, checking the relative positions and motions of the aircraft and the ship anticipating the possibility of manual override. If the pilot does not see visually something which seems familiar and confortable, he will take control of the situation very quickly, especially when he considers the consequences of allowing a faulty automatic landing system to maintain control too long. Thus, the automatic guidance and landing system engineer must consider during the design stage what the pilot wants to see and plan accordingly.

CONCLUSIONS

A number of conclusions have emerged during the course of this study. Although many of these findings have already been presented in preceeding sections of the paper we would be remiss if we did not gather them together under a single heading. There has been no real attempt to list them in order of importance beyond the authors' subjective judgment. All of the conclusions are supportable by the research and

analyses which collectively comprise this study. In some cases, the scope of this paper precludes inclusion of all supporting evidence for all conclusions. The references, however, provide ample information for the interested reader.

- A logically and mathematically sound methodology for estimating field of view requirements has been developed.

- The resulting field of view requirements depend in a critical way on the predicted model of the ship's airwake disturbance environment. Validation of the airwake environment for VSTOL operations with aviation facility ships is therefore imperative. If airwake turbulence should prove to be as upsetting in reality as the present model suggests, the aircraft will need high authority, high bandwidth flight control systems in order to function effectively in this environment . . . much higher than is typical of current helicopter practice.

- Based upon the analyses performed, it appears that the pilot probably could not obtain a satisfactory level of hovering precision in the conditions considered without either active gust alleviation devices or an overall reduction in gust velocity level. The latter could be achieved with a reduced wind-over-deck.

- It is desirable, from the standpoint of reducing field of view requirements, to provide visual cues and visual landing aids above the hangar for assisting the pilot in arresting the approach and providing hovering guidance.

- The constant relative bearing approach trajectory appears preferable.

In closing, we would like to mention that all aspects of the piloting problem discussed in this paper are currently under investigation by the U. S. Navy. At one extreme, the behavioral sciences are concerned with the fact that the specific nature of the perceptual cues used by a pilot to guide and control an aircraft in contact flight are unknown, although perceptual theory suggests that they are primarily visual and could be determined by appropriate experimentation. Previous attempts to specify the actual visual cues used in contact flight have been unsatisfactory possibly because of the complexity of the problem and because of the predominantly theoretical nature of the investigation.

In a more hardware directed development, the Navy Vertical Take-Off and Landing program is pursuing multiple goals all oriented toward providing improved approach, hoever, and landing capabilities of Navy and Marine Corps VSTOL aircraft. Included within this very broadly stated goal are separate efforts to develop integrated flight controls and display systems, landing guidance systems, visual landing aids, piloting techniques and procedures, and ship motion forecasting techniques. It is to these ongoing investigations in both the behavioral and engineering sciences that the field of view methodology can contribute.

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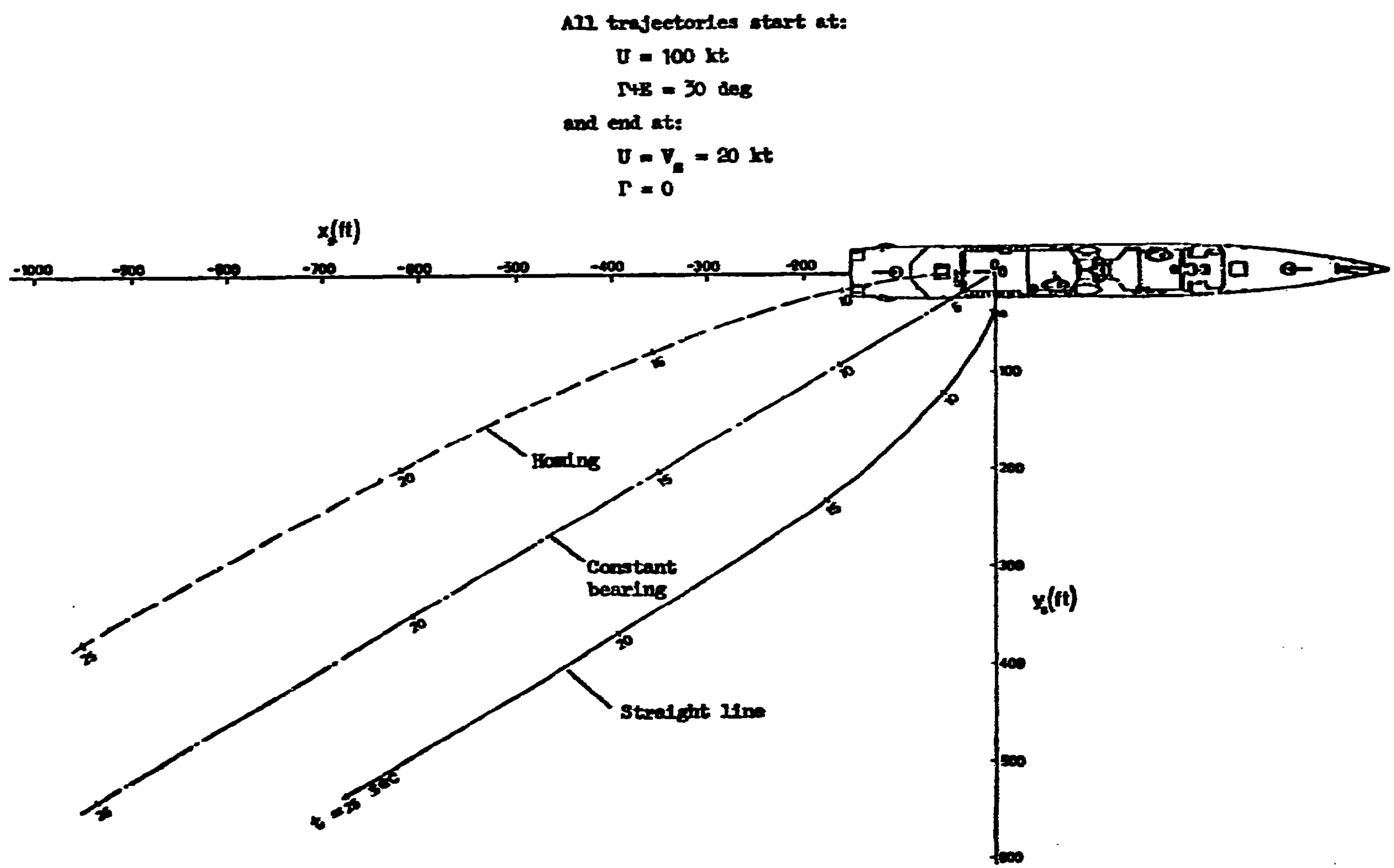


Fig. 1(a) Horizontal plane trajectories in ship frame

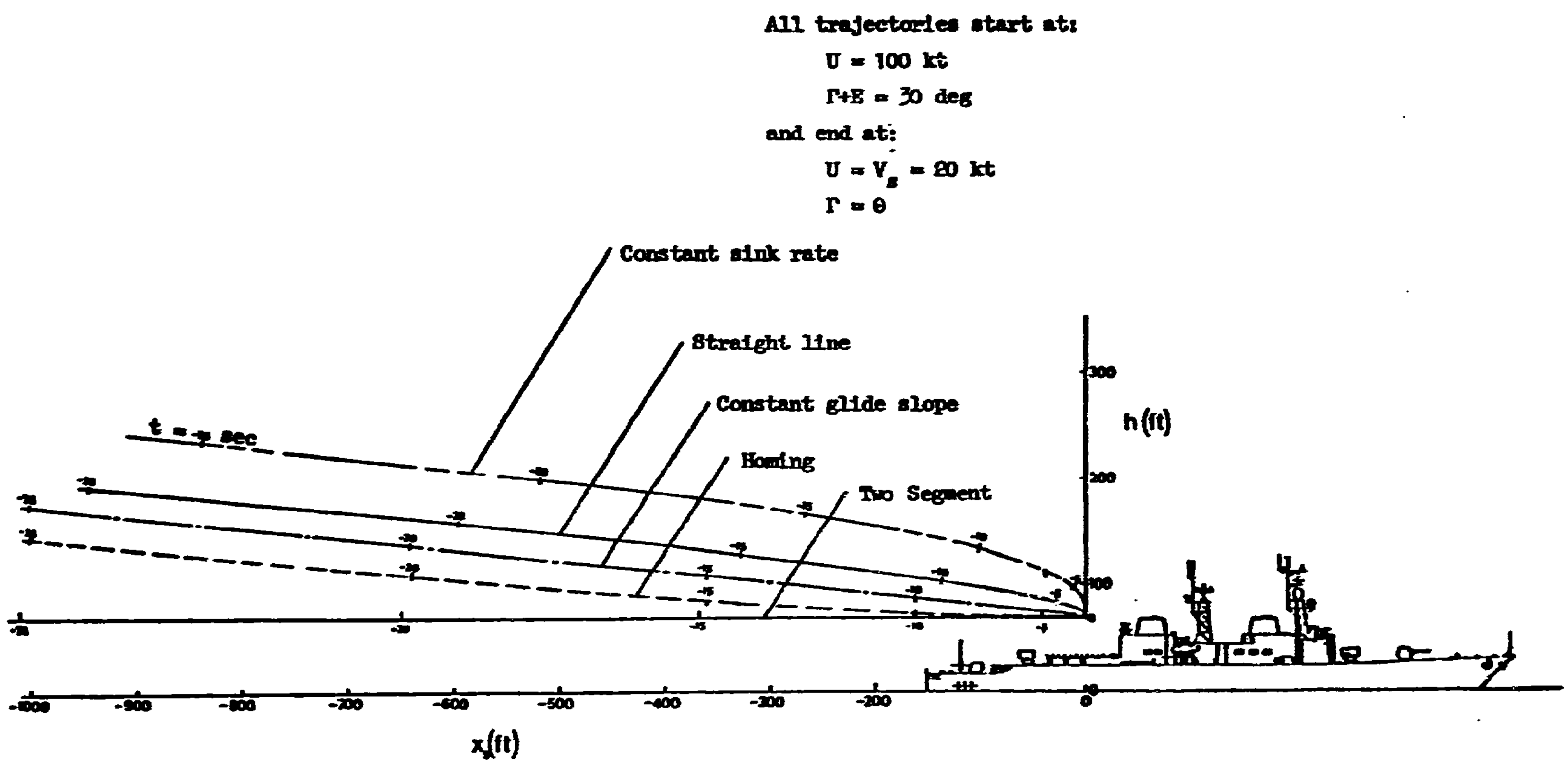


Fig.1(b) Vertical plane trajectories in ship frame

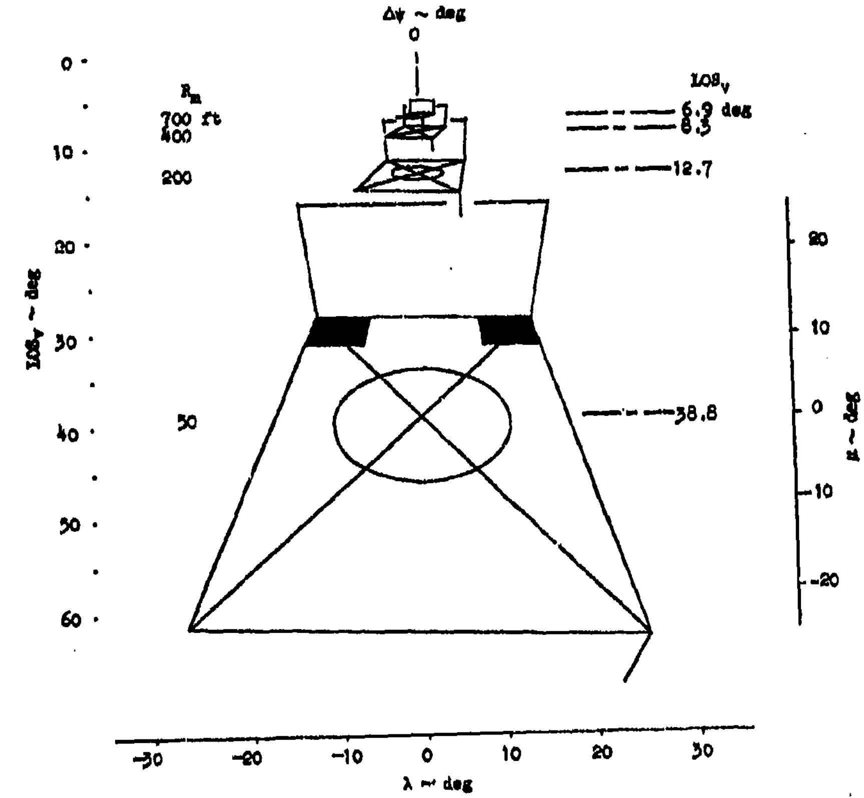


Fig.3 Perspective views of landing pad for a straight line trajectory

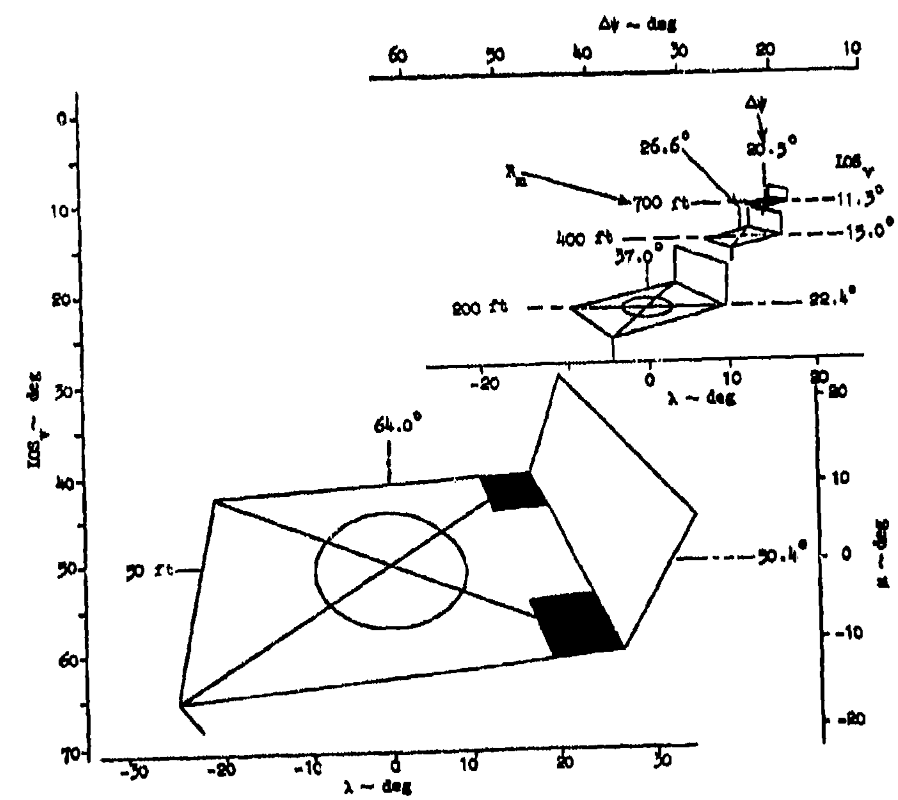


Fig.2 Perspective views of landing for a homing trajectory

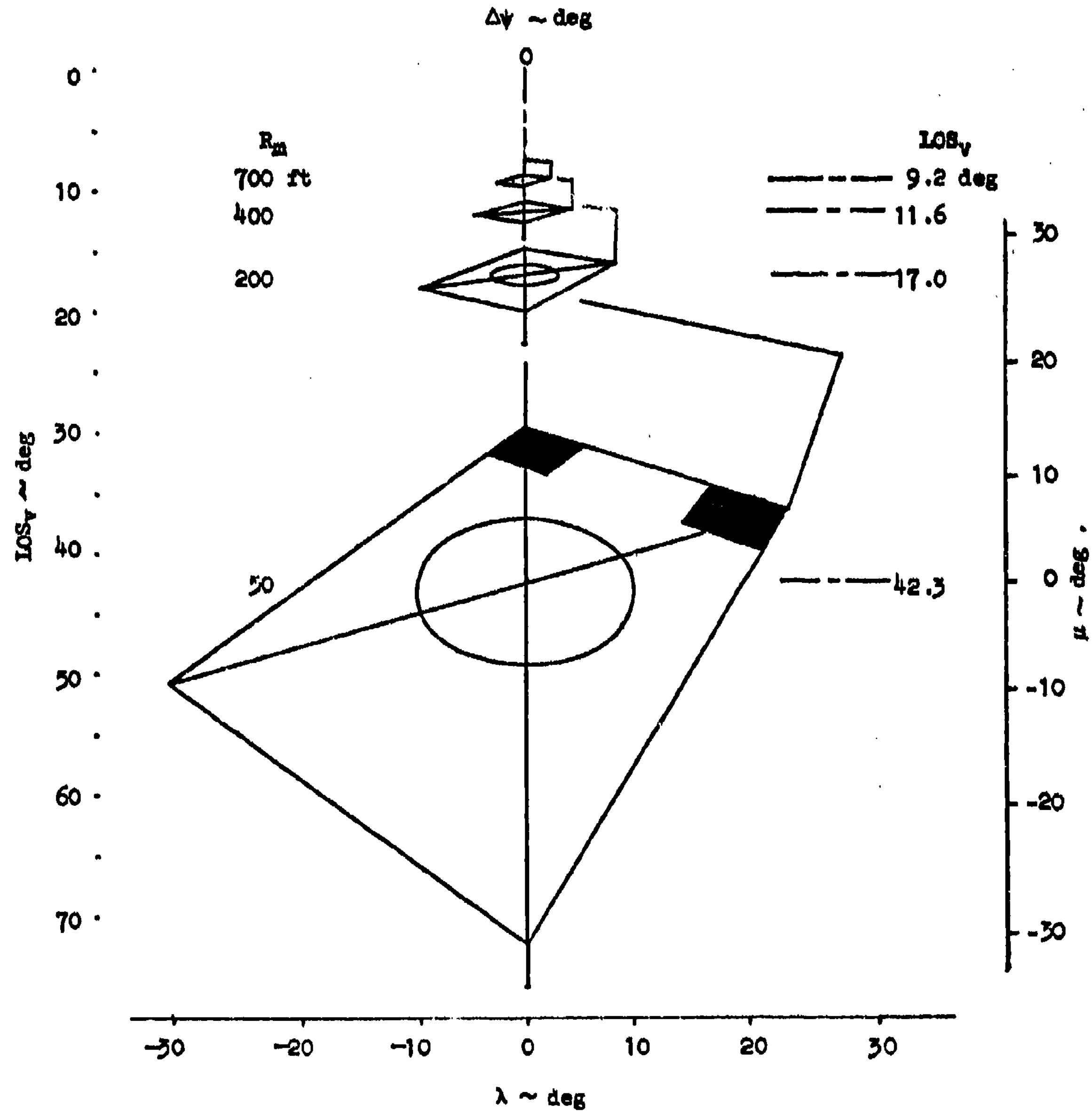


Fig.4 Perspective views of landing pad for a constant bearing trajectory

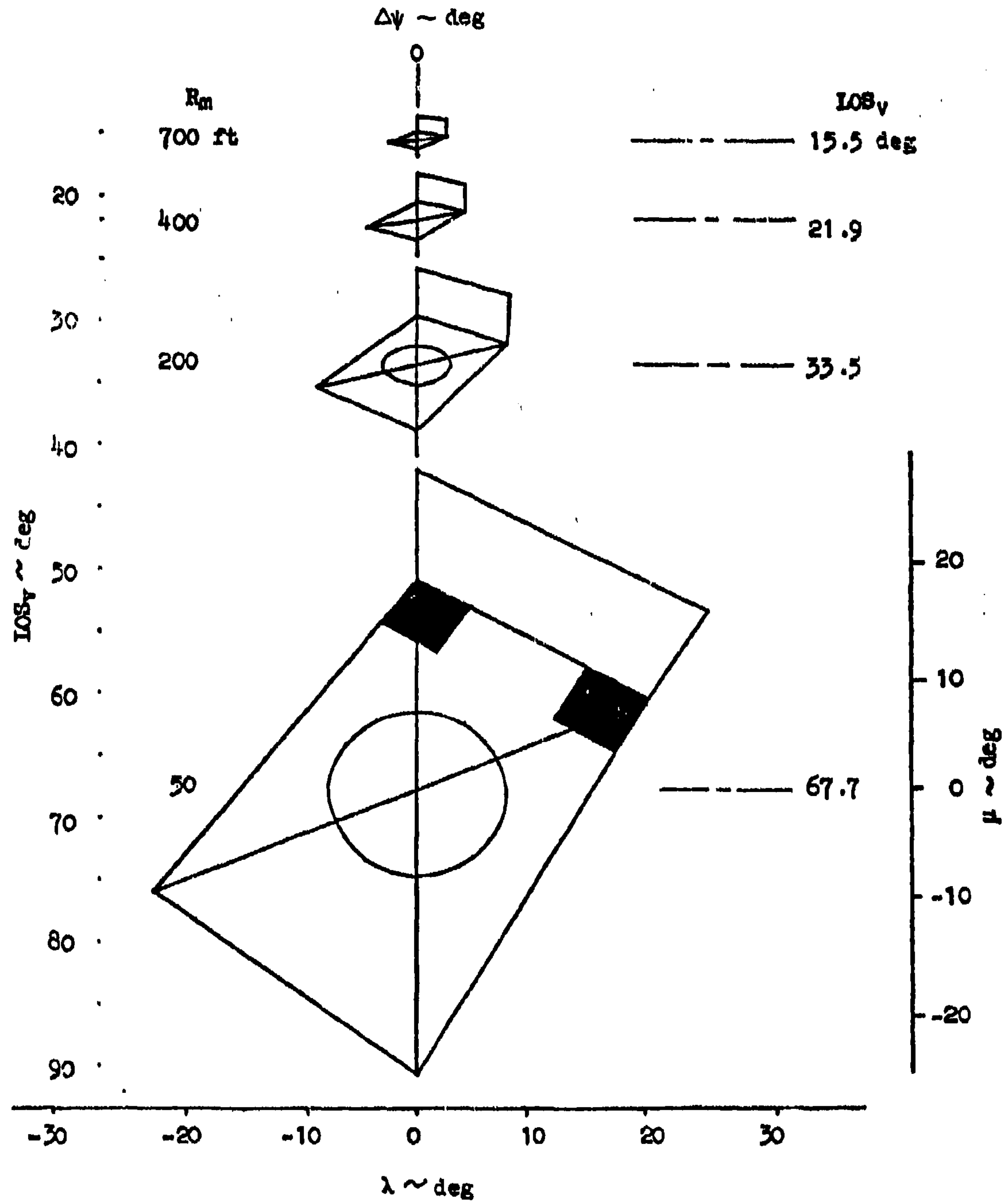


Fig.5 Perspective views of landing pad for a constant sink rate trajectory

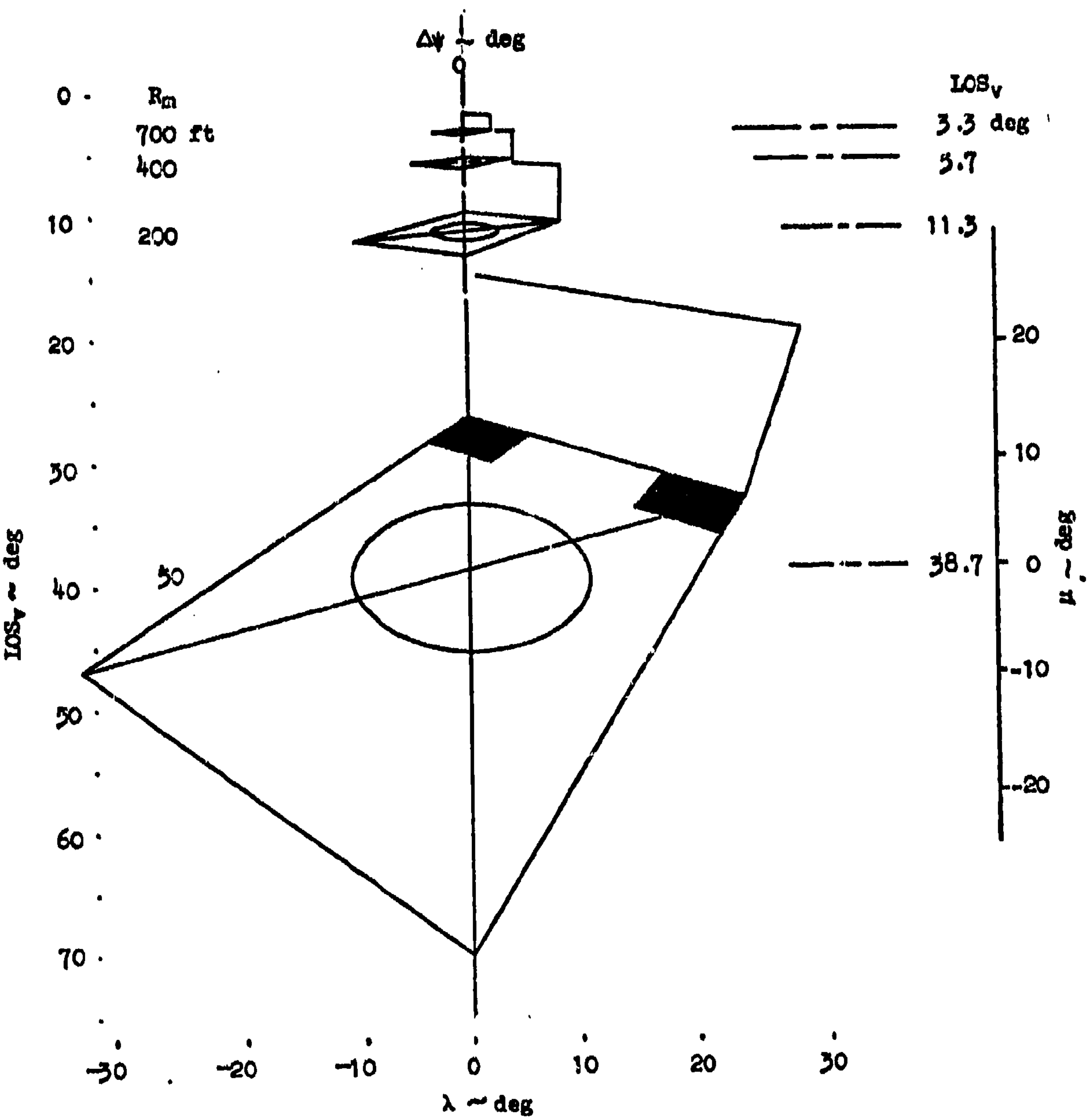


Fig.6 Perspective views of landing pad for a constant altitude trajectory

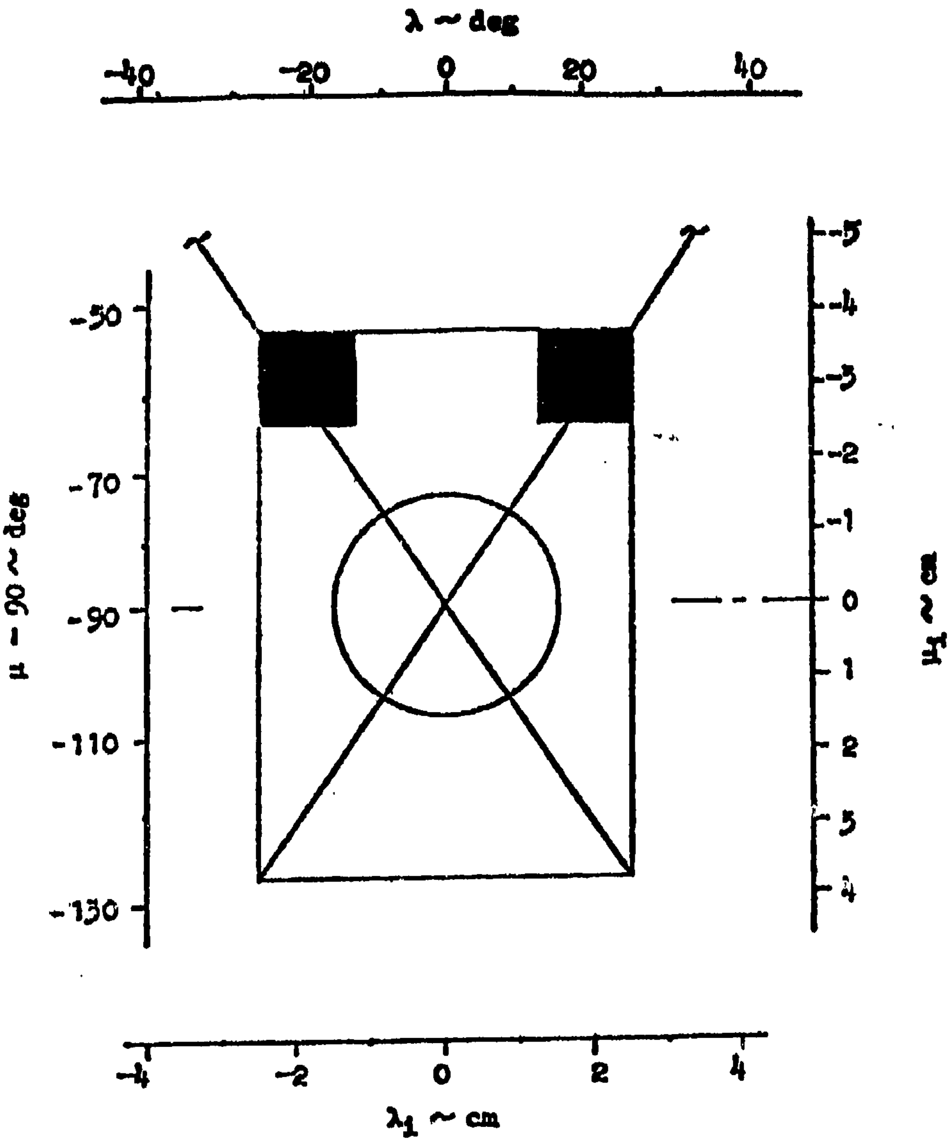
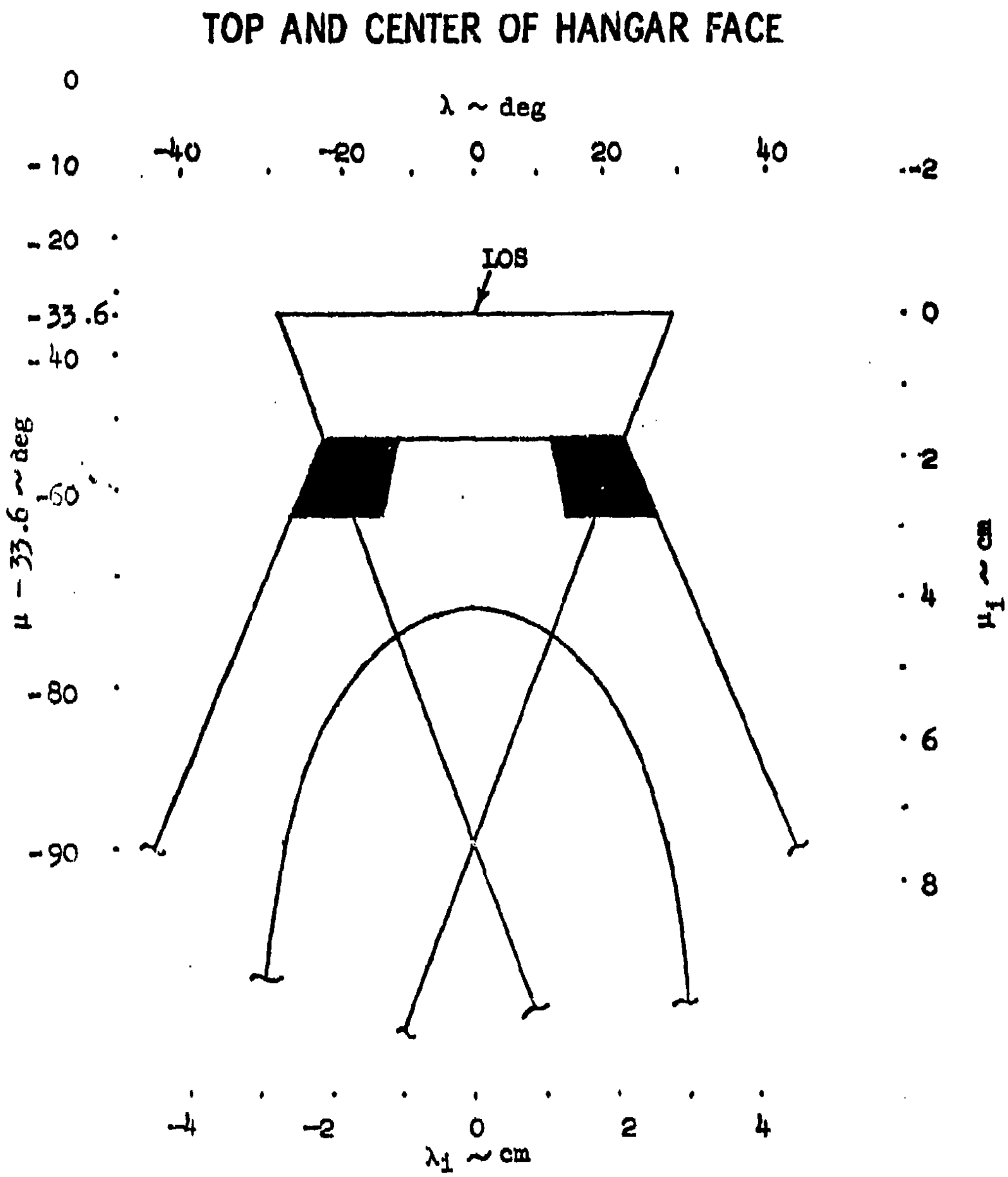


Fig.7 Perspective view of landing pad for aircraft 40 ft above landing pad and line of sight through center of pad



Sander's "Scanning Controller" for Head and Eye Motion Direction:

< 20° from foveal axis — Eye need not be moved

20°-60° from foveal axis — Eye moves with 1 dominant saccade

> 60° from foveal axis — Eye + head moves

Fig.8 Perspective view of landing pad for aircraft 40 ft above landing pad and line of sight through top and center of hangar face

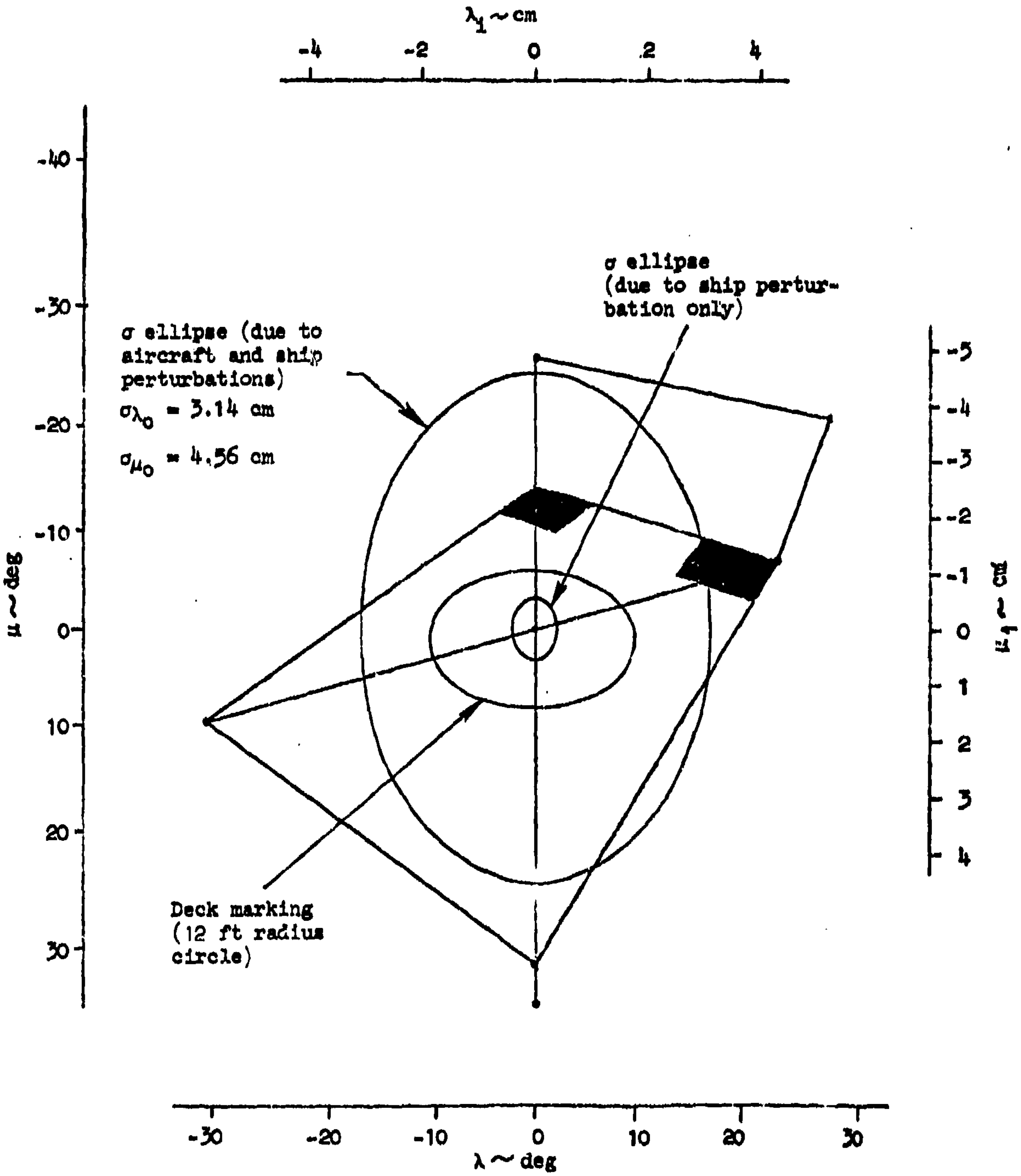


Fig.9 1σ variation in field of view for the R_m = 50 ft case

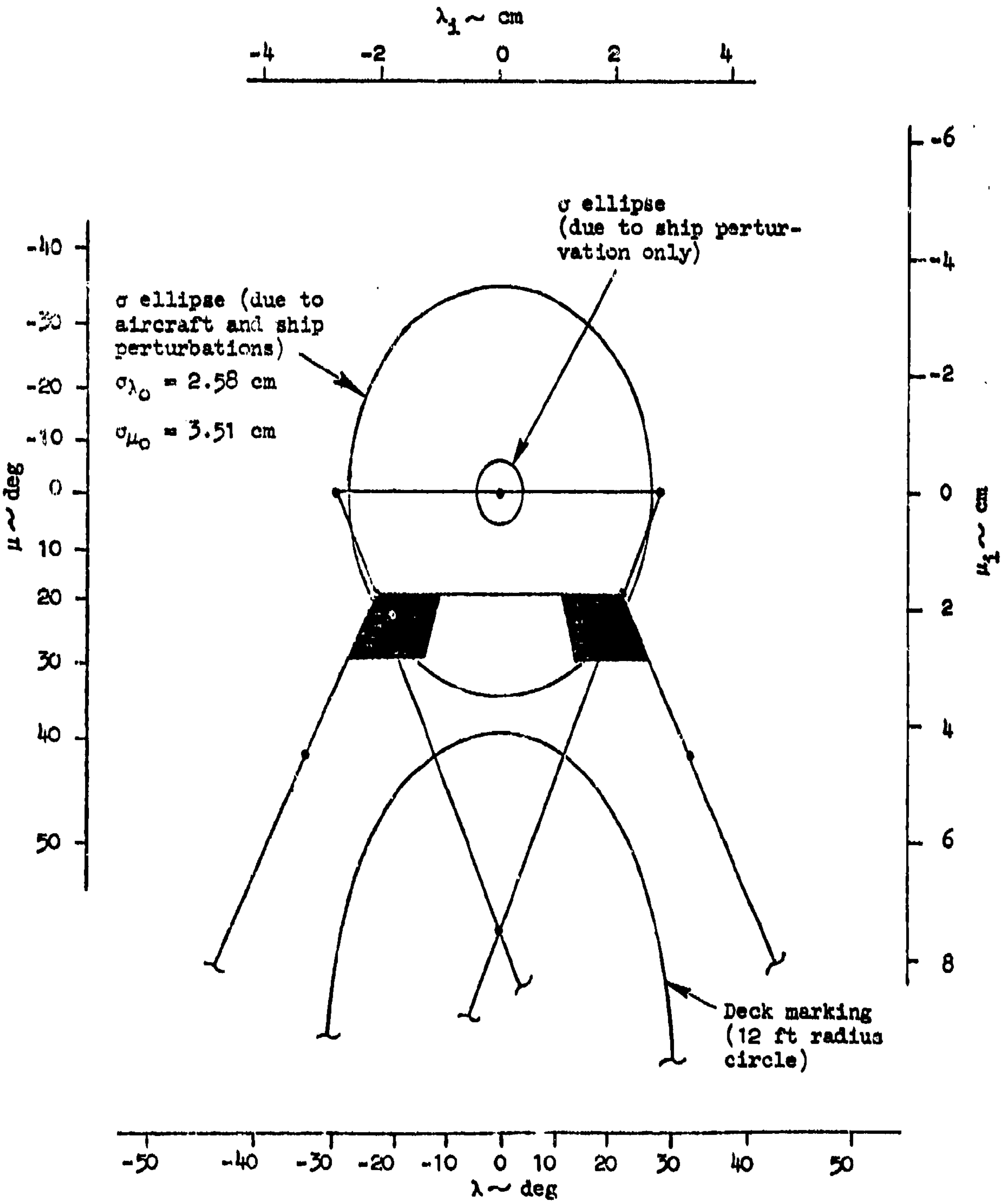


Fig.10 1σ variation in field of view for the $R_m = 0$ case

APPENDIX A

SESSION I DISCUSSION

Paper No. 2 and 3 (Professor Sargent)

Comment by Dr. L. Beck, Standard Elektrik Lorenz AG, Dept. CNS/TWB, Hellmuth-Hirth Strasse 42, 7000 Stuttgart, 40, Federal Republic of Germany:

Could you give us some comparison of computer run time efficiency among the simulation languages you mentioned?

Author's response:

I do not know of any completed studies comparing the computational efficiency of simulation languages. There is currently an effort at the University of Lancaster in England by David Ellison and John Crooks to compare several general purpose simulation languages. I do know that GPSS/H runs approximately five times faster than IBM's GPSS V. Please remember that computational efficiency is only one of the factors to consider when selecting a simulation language.

Comment:

Will new computer architectures such as array processors help to increase the speed of simulations?

Author's response:

I do not know of any simulations performed on an array or any other special type of computer. Currently there are research activities investigating how to have simulation performed on different computer architectures. At the first International Conference on Distributed Computer Systems held October 1-5, there was a paper investigating how to perform simulation on a distributed computer by R. E. Bryant of MIT; at the International Symposium held in August 1977, there was a paper by M. Parent of I.R.I.A. Laboria in France describing their efforts to investigate building a special computer for simulation; and I had a Ph.D student whose research was on investigating the use of an associative memory and a random access memory for use in performing simulation.

Paper No. 4 (Dr. Franke)

Comment by J. G. Wohl, Program Chairman, The MITRE Corporation, P.O. Box 208, Bedford, MA 01731, U.S.A.:

I have heard the test of a perfect bureaucracy defined as follows: If you turn off all of its inputs, will its outputs continue as though nothing happened? I have sometimes had the same thought with regard to some large-scale simulations. Dr. Franke, what has been your experience?

Author's response:

My experience has been that the validation problem is always with us. On the other hand, large-scale simulation is particularly helpful in understanding the integration of technical and operational problems. There are limitations; in particular, the time and funds available to perform the simulation and the correlation between the simulation and the real world must be considered. But in my experience, large-scale simulation relative to large-scale system development program is very cheap.

Paper No. 5 (Mr. Leedom)

Comment by Dr. H. A. F. Roefs, National Aerospace Laboratory, NLR, Voorsterweg 31, Emmerloord, Netherlands:

Could the use of "human gamers simulation" indicate where and how we should go in the future: more centralization of the decision process at higher echelons or more delegation to lower levels? And how would this relate to the type of conflict, such as air defense vs. guerilla warfare?

Author's response:

We already accept the notion that a C^2 system tends to exhibit a distributed decisionmaking process. One emphasis given to TAC ASSESSOR was the need to explicitly portray each individual C^2 element so we could observe the distributed (or noncentralized) nature of the total system. Our research to date is not complete enough to suggest the degree of centralized C^2 needed. As to the use of human gamers, we have found that this is an expensive approach to simulating distributed C^2 systems. This is because of the large personnel and facility resources required. The artificial intelligence approach is a much less costly approach to simulating and studying distributed C^2 systems. The questions of "what degree of centralization is required" is influenced by a number of factors. Among these are:

- The scope of information available at each level in the C^2 hierarchy

- The degree to which the information is fused, filtered, and tailored to the "problem structure" assumed at each level in the C^2 hierarchy
- The availability and vulnerability of communication links between each level of the C^2 hierarchy

As one can see, the answer to this question depends upon both human factors and technical factors. One also needs to tailor the answer to different combat environments. The interdependency, or interaction, among the human components, technical components, and the combat environment suggests the need to simulate this entire system. The simulation needs to reflect a high fidelity combat environment to "drive" the cognitive processes. The simulation also needs to faithfully represent the vulnerabilities of the C^2 system hardware. It is through this type of total simulation that answers will be developed to the centralization question.

Comment by J. G. Wohl, Program Chairman, The MITRE Corporation, P.O. Box 208, Bedford, MA 01731, U.S.A.:

I'd add just one note to Mr. Leedom's answer. In the U.S. there is a small movement underway to develop a taxonomy of tactical decisionmaking. Army, Marine Corps, and Air Force researchers are attempting to make explicit some of these "hidden" decision rules and heuristics.

Comment by Dr. J. Orlansky, Institute for Defense Analyses, 400 Army Drive, Arlington, VA 22202, U.S.A.:

Decision and cognitive science data deal primarily with individual decisionmaking. Command and control centers are concerned mainly with group decisionmaking, which may also be called bureaucratic decisionmaking. How do you propose to go from individual decisionmaking to "bureaucratic" decisionmaking in your simulations?

Author's response:

At this point in our research, we are just beginning to understand where individual and group decision processes occur (or predominate) in a C^2 system. One issue we are focusing on is the influence of organizational procedures (or lack thereof) on decision processes. We know that different commander or battle staff personnel exhibit unique decision styles. What we are attempting to define is the degree of variability of these processes for each of the key combat decisions. I believe that, in some instances, organizational procedures would tend to influence decisionmaking to a great degree. In other instances, primarily at the higher echelons of the C^2 hierarchy, individual cognitive styles would predominate. We must be careful not to build "average" C^2 systems which perform poorly when exposed to a particular commander style.

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

What part does learning play in the simulation of human thought?

Author's response:

At present, we have not included "learning" features into the TAC ASSESSOR model. One technique employed in the model, signature tables, can be applied in a more general form to include learning. Applications of signature tables to computer chess models have included the modification of coefficients, based upon historical data generated by the model, itself. Thus, we expect to address this feature later on in our research.

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

To what extent is time stability considered?

Author's response:

At present, we have not formally addressed the subject of stability. Our approach (which is based upon event-stepped simulation) recognizes the importance of transient phenomena. I believe that many unstable solutions are possible, depending upon the availability of communication links, the quality of the perception algorithms, and the quality of the planning and controlling logic. It remains, however, what instability we will actually find.

Because we believe that some C^2 systems might be unstable, we have rejected more simplified, closed-form solutions of the C^2 effects. Again, we are not trying to optimize C^2 performance, per se; we are first attempting to find out how real C^2 systems work.

Comment by Dr. L. Bock, Standard Elektrik Lorenz AG, Dept. CNS/TWB, Hellmuth-Hirth Strasse 42, 7000 Stuttgart, 40, Federal Republic of Germany:

Is your decision simulation adaptive to different environments or situations?

Author's response:

We have made a conscious effort to construct decision logic (production rule systems, signature tables, etc.) which are independent of specific scenarios or situations. Other models which I have observed in this same field tend to have scenarios and objectives embedded within the decision logic. This feature requires extensive changes to the decision logic whenever the scenario or combat situation is modified.

Comment:

Can your simulation be made adaptive in the absence of a complex learning ability?

Author's response

The TAC ASSESSOR model, in its present form, does not feature learning. One techniques used (signature tables) has been applied in the past to computer chess programs. Learning techniques can be incorporated into this technique and even programmed to rely on historical data generated by the simulation model, itself. I envision that learning features will be addressed by our study effort in the future.

Comment by J. H. Powell, Advanced Projects Dept. British Aerospace, Warton Aerodrome, Preston, Lancs, United Kingdom:

At the beginning of the lecture, it was stated that not all human decisions were rational (in the sense of being consistent with the "view" held of the game at the time of the decision).

1. How does the degree of rationality alter with stress, both physical and in terms of the urgency of the decision?

2. Does the very nature of the decision process alter with these stress levels and if so in what way?

Author's reply:

Stress and a sense of time urgency tend to reduce the complexity of the decision process. Using Soviet technology, stress would tend to move one from more complex cognitive processes (axiomatic or analytical thought) to more simple ones (empirical thought). We need to account for this type of shift in our simulation of thought processes. Under stress, thought would become less rational in the following sense:

- Fewer problem variables would be acknowledged and used to influence a solution

- Objectives would be reduced in a complexity

- A search for a satisfactory problem solution would be less exhaustive

Comment by J. G. Wohl, Program Chairman, The MITRE Corporation, P.O. Box 208, Bedford, MA 01731, U.S.A.:

A useful reference on the subject of decisionmaking under stress is a book entitled "Decision Making" by Janis and Mann.

Comment by R. J. Morrow, British Aerospace, Dynamics Group, P.O. Box No. 77, Bld 1bV, Filton House, Bristol, BS99 7AR, United Kingdom:

How do you create a true measure of utility for your simulation, so that you have a goal towards which to move?

Author's response:

Remember I said there were two types of measures, those internal to the command and control system having to do with performance, and those external to it having to do with utility or effectiveness. Effectiveness is measured by such parameters as attrition and exchange rates, and whether the Forward Edge of the Battle Area is moving toward or away from us. Obviously such measures are influenced by numerous factors other than command and control, such as force ratio and weapons effectiveness. But there is a third type of measure which we are just beginning to understand is needed. If one really wishes to understand the utility of a particular command control capability, one must also look closely at the human decision process involved. That is, in addition to taking the performance and effectiveness measures, one must also identify the key decisions made by a commander and assess how well they can be made both with and without some specific command and control capability. We don't have a precise definition of this intermediate measure yet, but it is related to how well a piece of hardware or command and control capability supports key decision processes. All three types of measures are needed.

Paper No. 6 (Dr. Saib)

No comments.

SESSION II DISCUSSION

Paper No. 7 (Ms. Hollinde)

Comments by Mr. D. Leedom, Headquarters USAF/SAGR, Washington D.C. 20330, U.S.A.:

Have you found a systematic means of assessing the commander's real information needs? Do you find commanders asking for more information than they really need to conduct successful operations?

Author's response:

No, we did not find any systematic means. In German forces regulations exist about how to state information needs. Commanders have to write information concepts in a given structured form, but do not succeed very well in doing so. They generally asked for less information and then discovered that they needed more. Using conventional information flow, they either get a mass of information or nothing because of competence problems. So they tend to rely on intuition. But when they see that they can get structured, selected information by CCIS, they start asking for more.

Comments by Ir N. Van Driel, N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands:

Is EMFIS intended for specific military actions or for optimization of the overall task of the Army/ Air Force? Also, is it intended for continuous monitoring within the military of various activities?

Author's response:

EMFIS is an experimental system, supposed to analyze and train in the use of CCIS. It consists of a system part and various user models. The system part is structured to support the C^2 process in the static headquarters, but more at the operational level than the tactical level. The main user model is tailored for situation monitoring of the overall military situation for political decisions. So, for the first part of the question the answer for the time being is "no"; for the second part it is "yes" for the given objective.

Comments by A. Bömisch, IABG, mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

What are you doing to live within the existing time constraints with the poor transmission quality of existing data circuitry?

Author's response:

EMFIS is an experimental system. So, because of the limited budget not too much emphasis was put on survivability.

Comment:

Are you using alternative routing and special protocols?

Author's response:

The system will normally utilize German PTT permanent phone lines, especially the TTY lines which in case of break down can be altered to another route by the PTT. It can also utilize military radio communication links in permanent mode. This is not what we would recommend for future operational systems, because of cost and lack of survivability. But systems like a packet-switched communication network are not yet available and still have technical and procedural problems.

Comment:

Are the same data links used for data acquisition and command control messages?

Author's response:

Each user can be a reporting or querying user in the frame of his function. In addition, there is a punched paper tape input/output interface to the conventional communication (TTY) network of the Bundeswehr for reports (data acquisition) and orders.

Paper No. 8 (Mr. Hutter)

Comment by Ir H. A. T. Timmers, Panel Chairman, Head Electronics Dept. N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands:

What have you done so far in validation and verification of the model?

Author's response:

Verification and validation before completion appears to be rather difficult if not impossible. Our model, however, is as I said, nearing completion in its first version. Efforts have been planned in the areas of

- Hardware test/comparison
- Data collection in operational systems

Comment:

Does the interest expressed for the model come from the scientific field or from the military field?

Author's response:

Sincere interest has been expressed from both sides as the model will fill in a "white spot" in the array of air defense models, at least nationally. Military users, of course, will accept the model only after a verification and validation process as scheduled (i.e., "proof of principle").

Comment by Dr. H. Kuersten, Assistant Scientific Advisor to SACEUR, SHAPE, Mons, Belgium:

On which level of national or NATO command have the operational requirements (i.e., information needs, communication lines, warning, etc.) been established for your simulation of overall Air Defense Command and Control? How do you intend to allow for the same platforms, sensors, bases, etc. in multiple missions? in mutual interference (IFF, EMC)? in air space deconfliction?

Author's response:

The model as presently developed is restricted to air defense C^2 up to the SOC/ADOC level; thus the problem of assignment of multimillion aircraft to attack or defense cannot be solved by the model but must be input. Information requirements on the various levels of AD-C^2 will be typical results of analyses supportable by this model rather than input to it.

ECM (SOJ, CBJ, SSJ, ESJ, CHAFF) are represented in the model as is procedural IFF by hostile criteria. SIF identification will not be sufficiently modeled as long as there is no reliable performance data on those systems, which is presently the case. "Air space management" will remain reserved to future extensions of the model which will not be done before the Air Defense version will have proven valid and applicable.

Comment by F. Herzmann, ESG Elektronik System GmbH, Postfach 80 05 69, 8000 München, Federal Republic of Germany:

Can you give us an idea about the increase of weapon system effectivity by the application of C^3?

Author's response:

Presently not; however, the model described has been actually designed to give an answer to this type of question.

To my knowledge, there is no study available which really quantifies the C^2 weapon system effectiveness equivalent in a broader sense (e.g., overall air defense). One early example is the STC study on fighter performance with/without AWACS being implemented. But this study was limited to A/C weapon systems.

Paper No. 9 (Lt. Col. Lynch)

Comment by Professor R. G. Sargent, Department of Industrial Engineering and Operations Research, Syracuse Univeristy, 441 Link Hall, Syracuse, N.Y. 13210, U.S.A.:

Systems in use today are continuing to increase in size and complexity with the result that when a failure or failures occur, we lose the total system independently of how they are designed to avoid this. An example of this is the power industry in the United States. You have not addressed this in your presentation on C^3 systems and my question is, Is this being investigated?

Author's response:

Your question really concerns the maintainability and survivability of C^3 systems and, what is more important, their impact on military worth. Both are accounted for in the above modeling effort. Though maintainability is important, survivability is even more so. The vulnerability of each C^2 site to offensive weapons and their accuracy is included in the model. C^3 systems have a high targeting priority by the threat. All of these synergistic effects are in the model and impact the military worth of the C^3 system.

Comment by C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

How do you ensure the flexibility and the continued validity of a monolithic centralized model?

Author's response:

I agree that this is necessary and we recognized the need very early. At the outset of this development we began briefing the DADENS-C^2 model characteristics to many groups within the Air Defense community, at all levels. Inputs were obtained from these groups and appropriate changes made. The resulting model flexibility is such that it can accept a wide variety of changes in system concepts and tactical situations. Hence, its expected lifetime is at least 10 or 15 years.

Paper No. 10 (Mr. Wilhelm)

Comment by Mr. A. J. Maclumpha, Royal Air Force Institute of Aviation Medicine, Farnborough, Hampshire, United Kingdom:

A lot of people have spoken about the presentation of necessary information. Have you assessed what information is necessary for effective task performance?

Author's response:

This is certainly a valid question, but as I said in the presentation we are just starting to put the human decisionmaking capability back into the simulation, and one of the more important questions to be approached is exactly your question. This is an area which certainly deserves further research.

Comment by Dipl. Ing. R. Hutter, Industrieanlagen Betriebsgesellschaft mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

When putting the man-in-the-loop and trying to assess future (1990) weapons and C^2 systems, you will find:

a. Experienced commanders from presently operational systems

b. Experienced engineers of future systems

c. Nobody experienced in the operation and C^2 of those future systems

How will you find people with the required qualification in (c)? If you don't you will never know whether your model is working close to the C^2 optimum or far away.

Author's response:

The simulation setup planned is of an experimental nature and should serve primarily as a tool for providing a better understanding of the problems involved in human decisionmaking for battle management in the air defense system. This being the case we do not plan to bring commanders with experience on presently operational systems into the game at an early stage of development. The first test runs will be performed with scientists from our own establishments who are familiar with the state-of-the-art.

After having established the validity of the methodology and of the man/machine interface, we might invite one or several experienced military commanders to participate. What the results will be I don't know at the moment; I am quite confident, however, that the human adaptability and capability to learn will permit us to carry out the experiments we have in mind.

Additionally, I would like to emphasize that this man-in-the-loop simulation is supposed to be an intermediate step which hopefully will enable us to design algorthms describing human decisionmaking that should replace those algorithms which are currently implemented in the model and which are lacking adaptiveness, are notoriously rigid, inflexible, and represent only one of a whole set of possible strategies.

Comment by Mr. G. Wunderlich, Industrieanlagen Betriebsgesellschaft mbH, D 8012 Ottobrunn, Einsteinstrasse, Federal Republic of Germany:

Regarding Air Defense force size effect: What is your experience with respect to various avionics/armament on both sides (Example: multitarget vs. single target capability)? We found, for example, the multitarget capability to be a driving factor.

Author's response:

This question was the subject of a thorough investigation during the last 2 years, the results of which are classified higher than this meeting. This study is available at your organization, however. I agree that specific avionics/armament parameters may be important; however, they will certainly not change the first order impact of the force size.

Comment:

Regarding Air Defense target selection logic: Your presentation differs from your paper. You stated today that you always chose the "best" logic; but in your paper you indicated a random-type selection (i.e., Pilot's decision is not sensitive). Does that mean that you changed from the random-type selection? From our experience we found the target selection process to be very sensitive which seems to be in contrast to your experience.

Author's response:

Your second question is concerned with the target selection logic of the fighter pilot as implemented in the model. At no place in the paper is it stated that a random selection logic is being applied. All the paper says is that different types of selection logics were tested. The general result obtained from a large number of test runs indicated that other factors were of higher significance in determining trends than a selection logic, the rationale for which remains unvalidated in any case.

There seems to be a misunderstanding of the basic concepts of randomness and sensitivity. If a parameter used in a model is insensitive (compared with other parameters) it does not mean that this parameter is random.

You are referring to your own experience indicating somewhat different results. As I do not know what you investigated, I am not able to comment on this. Of course, I am interested to learn how you might have come to different conclusions.

Paper No. 11 (Mr. Wunschmann)

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

In a conflict in Central Europe each side will be both an attacker and a defender. What facility is available in the model to include the effect of both the attack and defense roles on the workload for each side? Also what can be done to quantify this effect?

Author's response:

Since ours is an Air Defense simulation, we do not simulate the effects of our own attacking forces. We have them in our threat scenario, we see them on our scopes, and we try to identify them. Thus we represent only a "slice" of the total conflict. But again I must emphasize that our simulation is meant to support primarily operational training rather than operations research.

Comment by Dr. J. Barrett, Head of Helicopter Displays Section, Flight Systems Dept. RAE, Farnborough, Hants, United Kingdom:

In your presentation, you showed a slide which gave an indication of the large difference in identification time between an operator who was heavily loaded and one who was lightly loaded. Could you clarify the different tasks which were being undertaken during the identification phase, and how you are attempting to quantify the workload on the operator?

Author's response:

The task of an ID operator includes:

- Comparison of track parameters with a decision matrix
- The appropriate switch actions for each individual track at the data display console (man/machine interface)

The time required to identify detected tracks is influenced by:

- The operator's training level

- The complexity of the decisionmaking process

- Design of the man/machine interface

At a certain track load even a well-trained operator cannot maintain track with the ID requests popping up at his console (saturation effect). These limits must be quantified for feedback into the system design, operations procedures, or training schemes.

Comment by Dipl. Ing. R. Hutter, Industrieanlagen Betriebsgesellschaft mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

The methodology described appears to be an excellent tool for validation purposes of operations research type digital models.

Author's response:

Yes, if the commercial firm needs the information within the scope of a contract with the MOD of a NATO nation.

Comment:

What are the manpower and cost involved in setting up and simulating sizable scenarios of the order of several hundreds of A/C targets?

Author's response:

To create a region-wide scenario (about 20 radar sites) about 3 months with 3-4 people are required. Cost estimates cannot be provided.

Comment:

Is the methodology applicable to: (a) future systems and/or (b) modifications to the present system?

Author's response:

The simulation preparation system by its design allows accommodation of future systems and can reflect changes to the present system by adding new program modules. Along these lines it is already envisaged to include the NAEW system and the U.S. national 407L system.

Comment by Mr. F. S. Stringer, Panel Member, Royal Aircraft Establishment (R177 Bldg), Farnborough, Hants, United Kingdom:

What degree of sophistication do you use to ensure that ECM effects are regarded as acceptable, to provide a more realistic contribution to the simulation?

Author's response:

ECM is still a very weak point in our simulation. We have a rough model of the effects, but we are still not satisfied.

Paper No. 12 (Mr. Muclumpha)

Comment by Mr. J. G. Wohl, Program Chairman, The MITRE Corporation, P. O. Box 208, Bedford, MA 01730, U.S.A.:

With regard to your real-time simulation of air traffic control, what lessons have you learned about the presentation of information for airspace management?

Author's response:

Throughout this conference many authors have discussed the need for appropriate presentation of information. However, when questioned about the way to assess the appropriate information to display, the replies have indicated a gap in the research. I am not that familiar with the studies examining airspace management in ATC, but it is unquestionable that display design must meet the perceptual and cognitive needs of the operator. Design principles can be suggested from existing knowledge of the perceptual processes of the operator. However, there does appear to be a lack of extensive research on the operational effectiveness of displays, a situation I would hope to see changed in the next few years.

Comment by Dr. J. Barrett, Head of Helicopter Displays Section, Flight Systems Dept. RAE, Farnborough, Hants, United Kingdom:

You said that task demands could not be directly equated to workload. Would you care to say what therefore is your definition of workload and how can it be successfully measured in the operational environment?

Author's response:

Workload has often been defined as the amount of effort required from an operator in performing a given task. However, this does not tend to be a workable definition. Part of this difficulty lies first in the level at which one considers workload. Are we, for instance, interested in the performance of an isolated task or the amount of effort needed for a day's work or the effort required over say, a week? Secondly, to what extent do the characteristics of an operator affect his workload?

To my knowledge there is no valid way of measuring workload on an operational environment. Much research has assessed the value of a secondary task technique as an indirect measure of workload. However, one problem with this is that one is never sure that the secondary task is not interferring with performance on the primary task. A recent symposium on the measurement of workload (Moray, 1979) concluded that no general measure of workload is available.

Comment by Mr. F. S. Stringer, Panel Member, Royal Aircraft Establishment (R177 Bldg), Farnborough, Hants, United Kingdom:

Can simulation be used to improve the perception of operators?

Author's response:

Perception is an active rather than a passive process. People attempt to place structure and organization upon their visual environment. Because perception is an active process, it can be manipulated. Simulation can be used to identify the perceptual cues which an operator uses to structure his environment. If one can identify these cues, then one may be able to manipulate the visual environment for more effective operator performance.

Paper No. 13 (Mr. Herzmann)

Comments by Dipl. Ing. R. Hutter, Industrieanlagen Betriebsgesellschaft mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

Calculation of jammer strobe interactions only leads to sufficient solutions in multiple ECM scenarios if the target is visible to at least three radars ("deghosting"). At low altitudes terrain masking denies triple coverage in most cases. What is your experience?

Author's response:

Due to the complete coverage of the entire surveillance area even for low flying aircraft, jammers can be tracked as well as normal radar-echo targets. For identification, the bearings of less than three radars are sufficient. However, the combination of normal-target tracking and of jammer triangulation must be presupposed to attain this performance.

Comment:

There are three major contributors to the "C^2 force-multiplier" factor:

- Avoid overkills
- Reduce 'reaction times'
- Emission control of active weapons sensors

How do these factors contribute individually?

Author's response:

The greater part of the force multiplier factor results from optimal coordination of weapon system engagement. This depends greatly on the number of targets passing. A single target for example will be downed without fire coordination. The factor reaches its maximum if the number of targets is equal to the number of weapon systems.

Paper No. 14 (Mr. Davy)

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

Does the user have the facility to access the information and general details of the SIMBOX units in a form suitable to allow for other types of usage not envisaged by the originators of SIMBOX?

Author's response:

Yes. The user can access any item of data via the use of simple user calls, at any time during the simulation run. Typical questions which can be asked are: What is the current position of aircraft x? How many missiles does aircraft x have left? What is the position of aircraft x as measured by radar y? Which airfield did aircraft x take off from? What is the beam shape of the radar carried by aircraft x?

Comment by Mr. R. J. Morrow, British Aerospace, Dynamics Group, P. O. Box No. 77, Bld 1bV, Filton House, Bristol, BS99 7AR, United Kingdom:

In SIMBOX, how do you cope with the basic inconsistency between deterministic modeling (which is needed to stimulate real equipment) and system modeling (which is needed to observe and to measure things)?

Author's response:

In SIMBOX as with all event-based simulations, events are taken one at a time, in proper time sequence but not in proper or real time. Thus, there is no way of stimulating real equipment with SIMBOX, since real equipment operates in real time and would have to be stimulated in real time.

SESSION III DISCUSSION

Paper No. 15 (Mr. Shanahan)

Comment by Dipl. Ing. R. Hutter, Industrieanlagen Betriebsgesellschaft mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

Is the differential equation type model "TAC PENETRATOR" still an applicable tool or is it today outdated by other USAF model developments some of which we learned from this meeting?

Author's response:

Results from the Air Force's TAC PENETRATOR model have not appeared in print for some years (according to HQ USAFE/ACS representative); consequently, it may be assumed that other, newer models such as those described at this symposium are being applied in its place. On the other hand, there is nothing to preclude the possibility of its being needed for some future study. Discussion with HQ USAF/ACS (Studies and Analysis) would be appropriate.

Comment:

Is further C^2 mission effectiveness modeling effort established at MITRE?

Author's response:

Concerning MITRE's C^2 (and C^3) modeling efforts, the Program Chairman, Mr. Wohl, would be more qualified to respond to this question, since his department at MITRE considers such topics as part of the C^3 architecture study process. Historically, MITRE develops or acquires from other agencies or from contractors such models and simulations as are appropriate in pursuit of MITRE's work programs. Since MITRE is in the C^3 business, it is reasonable to assume that MITRE has or can acquire contractor results from models and simulations in this area.

Comment by Mr. J. G. Wohl, Program Chairman, The MITRE Corporation, P.O. Box 208, Bedford, MA 01730, U.S.A.:

Under sponsorship of the Air Force Electronic Systems Division, a model is currently being developed by a contractor, CACI, for delivery to us by year end. This is a specially designed model, programmed in SIMSCRIPT II.5, for exploration and evaluation of alternative command and control system architectures. It includes a detailed C^2 submodel, plus a two-sided air mission submodel and a ground war model. Measures of C^2 effectiveness can be taken in terms of such factors as air mission effectiveness, attrition ratios, and FEBA movement.

Comment by Mr. B. Taylor, Marconi Avionics Ltd. Old Parkbury Lane, Coloney Street, St. Albans, Herts, United Kingdom:

During the early feasibility study stages of AWACS, was there an overall AWACS system model or was a more pragmatic approach taken involving radar subsystem optimization followed by data handling subsystem optimization?

Author's response:

There do not appear to have been any overall AWACS system models that had any real utility during the early AWACS Feasibility Study days. There is some evidence that the Air Force and certain contractors employed very gross analytical models (as opposed to computer models) to size various subsystems like the computer, the number of displays, and the number of radios to satisfy basic system missions. However, the disparity between the results of these analytical models and the E-3A configuration today indicates that these models had limited utility. To other approach of computer modeling the crucial subsystem, the radar, and then extending these models over time to include data processing, display, and communications, appears to have been the most widely used and fruitful one.

Comment by Mr. J. E. Freedman, Institute of Defense Analysis, 400 Army Drive, Arlington, VA, U.S.A.:

Please describe the steps taken to validate radar performance models.

Author's response:

Throughout their evolution, the E-3A Radar Performance Prediction models have been validated by comparing representative model outputs with actual flight test results, where available. As discussed in the presentation, early model predictions could not be validated because the radar was not yet developed. When the clutter data base from brass board was gathered and incorporated into the model in 1972, scaling and calibration functions for target conditions within as well as beyond the scope of the flight test program were derived so that model predictions would match those results which were gathered in flight. This process was repeated when even more extensive data became available from the DT&E flight test program. Again, analytical functions were derived to be consistent with flight test results for

those conditions under which flight test data were available for comparison. As data continue to be gathered through production system flight testing, refinements and added sophistications are made so that the model predictions match flight test results for a larger set of E-3A radar and target conditons.

Comment:

Have the radar models being used in the mission simulators been validated?

Author's response:

The radar models in the mission simulator are reasonable representations of radar performance for use in training, but they have not been validated to the same depth as the Radar Performance Prediction models discussed in the previous reply, nor do they really have to be validated further. In situations where only crew training is involved, the radar data generated by the simulator are adequate. In situations where radar performance realism is required or desired, such as mission analysis or crew proficiency assessment, data tapes from live exercises are used, and radar performance modeling is not needed or employed.

The other consideration in such an issue is the fact that radar outputs provided by the simulator do not indicate performance of the radar by themselves because the sizes (radar cross sections, etc.) of the targets are not provided. Consequently, the question of validation is rather moot.

Paper No. 16 (Mr. Newman)

Comment by Mr. F. S. Stringer, Panel Member, Royal Aircraft Establishment (R177 Bldg), Farnborough, Hants, United Kingdom:

Has the design of your system included the recognition of possible prolonged periods of flight in conditions likely to produce precipitation static, such as is generated by ice crystal layers in clouds? How is resynchronization of the Omega receiver simulated after a period of P-Static paralysis?

Author's response:

Precipitation static is highly unlikely to cause problems for the system because of the Omega antenna design (dual, orthogonal H-field loops). However, since the simulation facility injects simulated Omega signals as radio-frequency signals, the NCS can resynchronize at any time that either the operator or the operational program decides to do so. We can cause the NCS program to resynchronize by including an arbitrary period of high atmospheric noise in the simulation scenario through the noise bias function.

Comment by Mr. R. S. Vaughn, Director, Sensors & Avionics Technology Directorate, Naval Air Development Center (30) Warminster, PA 18974, U.S.A.:

The Air Force may well choose to expand the E-3A navigational functional group to include GPS NAV STAR satellite navigation and perhaps JTIDS grid navigation. What capabilities does the subject simulator have to accommodate such changes?

Author's response:

Expansion of the facility to accommodate outputs from GPS is no problem if we only desire to simulate the link from the user equipment (UE) to the Omega receiver computer. Similarly, integration of a simple JTIDS relative-navigation system interface would not be difficult. Naturally, new simulation would have to be developed for these functions; the modularity of the current design should facilitate such a task.

Paper No. 17 (Mr. Roome, presenter)

Comment by Mr. B. Taylor, Marconi Avionics Ltd., Old Parkbury Lane, Coloney Street, St. Albans, Herts, United Kingdom:

Have you addressed the problem of integration of JTIDS data into the data base with the consequent interoperability problems?

Author's response:

Yes, very much so. The Interface Adapter Unit on the E-3A handles all computer interfaces with onboard equipment, including TADIL links, IFF, and Navigation systems as well as with JTIDS.

Paper No. 18 (Mr. Easdale)

No comments.

Paper No. 19 (Mr. Alvarez)

Comment by Dr. H. A. F. Roefs, National Aerospace Laboratory, NLR, Voorsterweg 31, Emmerloord, Netherlands:

Could you indicate how the ATI simulator handles the tracks when the total number of targets exceed the capacity?

Author's response:

The capacity of the simulation model can be made arbitrarily large; thus overloading is not a problem. Overloading can, of course, be a problem in the operational program, and the ATI function must be designed with this in mind. During our development efforts, one of the key aspects of performance which was of interest was the total number of tracks (i.e., sum of potential, tentative, and established) in the system simultaneously. Conscious efforts were made to insure that the ratio of the total number of tracks to the number of targets in the scenario remained within reasonable limits. The insights gained during this study were useful in evaluating the track table capacities proposed by the contractor, which will provide adequate margin to protect against saturation.

Comment by Mr. F. Herzmann, ESG Elektronik System GmbH, Postfach 80 05 69, 8000 München, Federal Republic of Germany:

Which search procedure do you apply for quick association of a radar-derived plot to the correct track, stored among others in your track register? Do you check all tracks for every association?

Author's response:

For each track in the system, track association and correlation is attempted against all target reports (even those that have correlated with other tracks). After track association and correlation, any conflicts (i.e., a report correlating with more than one track) are broken to prevent a report from updating more than one track. Normalized residuals are used for determination of the "best" target report/track pair.

SESSION IV DISCUSSION

Paper No. 20 (Dr. Fields)

Comment by unknown source:

A pilot's maneuverability is unrestricted except by aircraft limitations; that is; he can make the aircraft go where he wishes. How many pictures do you take from any one point in your maneuvering area, and how do you handle the instantaneous discrepancy between the simulation flight path and the original photographing aircraft's flight path?

Author's response:

First, we take a number of pictures at every point. In the flight simulator system I described, we take four pictures: three at different angles and one looking at instruments. This is decided beforehand. Whatever pictures are initially taken serve to define and limit the flightpaths which the simulation is capable of reproducing. If you photograph a set of circlings, a set of takeoffs, and a set of landings, then you have the basis for the simulation. It's very easy to take these pictures, but it has to be carefully planned. The process takes one or at most two days to complete. Finally, it is not necessary to index each frame on the video disc. Rather we index each flightpath segment such as a single takeoff or landing. Also at path intersections we index the alternative directions. Thus discrepancies are held to a minimum and are entirely determined by how many different flightpath segments were originally photographed.

Comment by Mr. H. W. Pongratz, IABG Abt WTS, Einsteinstrasse 8012 Ottobrunn B. München, Federal Republic of Germany:

Did you consider the use of image distortion to allow the students some deviation from the preplanned flightpaths?

Author's response:

We have built the experimental equipment to include distortion in order to interpolate among flightpaths. However we did not include this feature in the system I described today because it greatly increases the cost.

Comment:

Have you tried to use available commercial equipment capable of higher speed response?

Author's response:

We have used equipment which is 10 times faster (e.g., multiple video disc players). This improves the system but again increases the cost. But even with the fastest equipment there are still small discontinuities noticeable when the flightpath changes.

Comment by Dr. R. G. Sargent, Department of Industrial Engineering and Operations Research, Syracuse University, 441 Link Hall, Syracuse, NY 13210, U.S.A.:

Could you use this technique in a training aircraft to compare the actual flightpath against stored images and determine when the student pilot is making a serious error?

Author's response:

That's a new idea that we had not thought of. It might be a good idea.

Comment by Dr. H. Kuersten, Assistant Scientific Advisor to SACEUR, SHAPE, Mons, Belgium:

The flight dynamics of an aircraft results in only physically realizable flightpaths. Is your system capable of simulating unrealistic flightpaths?

Author's response:

Remember that the pictures are taken from a real aircraft in flight. Therefore no flight path segment is stored which is not physically realizable. While it is true that one could construct unrealistic flightpaths from selected segments, our software does not permit such unrealistic paths to be constructed.

Paper No. 21 (Mr. Mascle)

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

Do you envisage the representation of threats such as missiles, cannon, and other helicopters in the near future? What is the time scale of such development?

Author's response:

Oui, nous pensons que ce type d'études est l'un de ceux où le SDVEM peut être le plus utile, en permettant de simuler des configurations de combat Air-Air, impossibles à réaliser au cours d'un vol réel d'essai.

Le temps nécéssaire à la mise en oeuvre d'une telle simulation dépend essentiellement de la complexité du combat que vous désirez étudier.

Comment by Mr. H. W. Pongratz, IABG Abt WTS, Einsteinstrasse 8012 Ottobrunn B. München, Federal Republic of Germany:

What field of view do you envisage for your simulator?

Author's response:

A propos du système de restitution de la vision du monde extérieur, il importe d dissocier le cas de la vision de jour de celui de la vision de nuit.

Comment:

What resolution do you envisage your visual system?

Author's response:

Pour le cas de la vision de jour, je ne peux rien dire à l'heure actuelle, ne disposant pas des résultats d'études en cours.

Comment:

Do you see a reasonable compromise between field of view and resolution requirements for a daylight visual system for low level flight?

Author's response:

Pour le cas de nuit, notre objectif est de mettre en place un système qui soit compatible avec les spécifications des systèmes optroniques envisagés pour les missions réelles de nuit.

Paper No. 22 (Dr. Orlansky)

Comment by Ir H. A. T. Timmers, Panel Chairman, Head Electronics Dept. N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands:

Do you have any idea where the data point would be in your first chart for the APOLLO flight?

Author's response:

It's difficult to comment on that. The NASA program was probably the most expensive flight simulation program ever imagined in the life of man, and they were not in any position to judge whether or not it was cost effective. They did everything they thought needed to be done and spent enormous amounts of money, but there's no way to determine how much it should have cost. The obvious remark is that it worked; but that's not proof. I have no way of evaluating what should have been done in the NASA program.

Comment by Mr. J. G. Wohl, Program Chairman, The MITRE Corporation, P. O. Box 208, Bedford, MA 01730, U.S.A.:

You mentioned in passing that there was some recent evidence on the utility of motion bases. Could you comment further on that?

Author's response:

This is a highly controversial issue on which people are polarized. In 1974 Jefferson Koonce compared the performance in the air of pilots trained in simulators with motion and without motion. He found that they performed equally well in both cases. The finding was a total surprise. No one had asked the question, Do you need motion? Does it make a difference? in 30 years, and motion was being included in flight simulators as a matter of course since pilots liked it. Koonce's finding was such a surprise that six separate studies were done to double check it. This was done for straight and level flight, for maneuvering flight, for high-fidelity vs. low-fidelity simulators, etc. The results were absolutely consistent: no difference. As a result, the USAF is procuring the A-10 flight simulator without motion bases.

Comment by Dr. C. I. Fields, Cybernetics Technology Office, Defense Advanced Research Projects Agency, 1400 Wilson Blvd, Arlington, VA 22209, U.S.A.:

Can you make similar comments about the visual fidelity?

Author's response:

Yes, but here we have no data. While a number of studies have been done to improve the visual fidelity, not one has been aimed at determining whether that makes a difference in performance.

Comment by Dr. H. Kuersten, Assistant Scientific Advisor to SACEUR, SHAPE, Mons, Belgium:

I wonder if you've noticed performance differences among pilots who went through these simulator courses with different instrument layouts, analog vs. digital displays, and more or less assistance from the ground in making maneuvers? The pilot's performance itself is not the whole answer; he has many inputs from ground-based C^3 systems.

Author's response:

Good question--we just don't have the answer to that yet. There are no data dealing with this subject.

Comment by Mr. H. W. Pongratz, IABG Abt WTS, Einsteinstrasse 8012 Ottobrunn B. München, Federal Republic of Germany:

Are technological improvements in visual simulation capabilities being developed?

Author's response:

Yes, they are coming along very fast in a number of companies that make visual systems. But I question how much of this capability is really needed in flight simulators.

<u>Paper No. 23 (Mr. Dreyfus)</u>

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

On the question of language, how much attention must be addressed to the problem of communication between programmer and analyst?

Author's response:

Lorsque nous réalisons un simulateur de vol à LMT, l'analyste est le programmeur sont la même personne. Nous avons constaté que le problème de communication était essentiel et que le meilleur moyen de le résoudre était que la communication se fasse au niveau d'une même personne. Actuellement nous utilisons principalement des ingénieurs qui font aussi bien l'analyse du problème que la programmation. Je pense que cette technique est utilisée d'une manière assez courante chez les autres constructeurs de simulateurs. Cependant un problème de communication existe souvent entre le fabricant du simulateur et le client, étant donné que ce dernier, lorsqu'il reçoit un programme le comprend beaucoup mieux si c'est un langage qu'il connait bien (à savoir le FORTRAN qui est très répandu et bien connu), plutôt qu'un langage d'assembleur.

Mais il se pose quand même à ce moment, le problème de la documentation au niveau des programmes. Par exemple, le FORTRAN ou tout langage évolué est auto-documenté, c'est-à-dire qu'en fin de compte les ordres sont dans un langage connu, donc facile à comprendre. Malheureusement ce n'est pas exact, parce que, en fait, le problème n'est pas de comprendre les ordres qui sont exprimés dans le programme, mais de savoir ce que représente chaque symbole dans le programme, et pourquoi telle expression est comme cela. Donc, un programme FORTRAN doit être très bien documenté et avoir beaucoup de commentaires. Il y a cependant un autre problème, celui de trouver les ordres FORTRAN,

c'est-à-dire qu'en fin de compte il y a dans un bon programme FORTRAN plus de commentaires que d'ordres. Il faut que le programmeur fasse très attention pour trouver une mise en page correcte de manière à pouvoir découvrir très rapidement le programme FORTRAN proprement dit. Sans cela, on ne voit que des commentaires. Donc, je pense que, si au point de vue compréhension des ordres c'est plus facile dans le langage évolué, ce n'est pas complètement immédiat; il faut donc passer un certain temps pour modifier un programme, qu'il soit en FORTRAN ou en assembleur.

Mais je suis d'accord avec vous, le FORTRAN est quand même un meilleur langage de communication que l'assembleur, et je répète que ce problème existe entre le fabricant et le client, mais pas au niveau du fabricant.

Paper No. 24 (Dr. Barrett)

Comment by Dr. H. A. F. Roefs, National Aerospace Laboratory, NLR, Voorsterweg 31, Emmerloord, Netherlands:

Isn't the binocular rivalry problem the same as the fatigue problem in medicine where doctors (and students) look for rather long periods of time through microscopes? As far as I know they are taught to keep the left eye open and the light level high, while using the microscope with the right eye.

Author's response:

This is absolutely true. As far as the monocular viewing system is concerned, if the light level into the other eye is equalised, the rivalry problem commences immediately, producing high fatigue. It is interesting to note that extensive work has been carried out in the United Kingdom on producing binocular viewing systems for microscopes because of this problem.

Comment by Mr. Grison, Centre d'Essais en Vol, B.P. No. 2, 91220 Bretigny-Sur-Orge, France:

Quelle échelle choisie sur la maquette?

Author's response:

The original scaling of 3000:1 was barely adequate for what we wanted to do. As a result, in our new simulation facility we are changing to a scale of 1500:1 and 1000:1 in order to improve the resolution. Remember that we were simulating a night vision system in which resolution was basically poor. So there was no point in trying to simulate a higher level of resolution.

Comment: Quels sont les problèmes rencontrés au niveau de la prise de vue au point de vue des asservissements?

Author's response:

We found that we required services capable of angular accelerations of $1000°/sec^2$. We used a low-smear camera system in which the readout was presented on an extremely short persistance P-43 phosphor. The result was an ability to simulate pitch and roll rates of up to 120°/sec representing a highly maneuvarable helicopter.

Comment by Ir N. Van Driel, N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands:

We heard earlier that a moving base simulator is not of much help. On the other hand you mentioned that the pilot when he moved his head, found himself lost. In that case could a motion capability of the simulator, as in a real aircraft, help the pilot to orient himself?

Author's response:

I believe that the problem in this case was caused by the fact that the pilot could not see any outside world information other than from the helmet display. In the real aircraft some elements of the outside world will always be seen, which will reduce this effect. The influence of motion cues, particularly from yaw in this case is very small. I do not feel, therefore, that the lack of this cue affected this problem.

SESSION V DISCUSSION

Paper No. 25 (Mr. Freedman)

Comment by Dipl. Ing. R. Hutter, Industrieanlagen Betriebsgesellschaft mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

Is the performance of the "Direct Subsystem (DSS)," e.g., SIF (MK X, XII) input to the testbed? If yes, is this data obtained from reliable sources or is it a parametric input?

Author's response:

The DSS performance will be described by a model which incorporates extensive analyses of the MK X and MK XII SIF performed by STC and be various U.S. agencies. These have led to a thorough understanding of the operation of these systems and their reaction to the operational environment. The model used to emulate these systems will have a high level of fidelity and will represent both main and higher-order effects, as it is recognized that this is essential to the credibility of the testbed.

Comment:

Is the testbed designed and intended as a system for the investigation/test/analysis of air defense issues other than the IFFN, e.g., configuration of C^3 sites, network, and DP alternatives?

Author's response:

Because the ISS is embedded in the C^3 system for air defense, it is necessary to have the testbed represent this entire C^3 system for an evaluation of identification to be performed. The creation of such an extensive facility will probably stimulate great interest in its application to broader purposes. We anticipate that the testbed may eventually evolve to be a theater air defense testbed, although there are no definite plans for this at this time.

Comment by Mr. J. G. Wohl, Program Chairman, The MITRE Corporation, P.O. Box 208, Bedford, MA 01730, U.S.A.:

An earlier paper indicated that it would take some 10 centuries to run through a complete simulation involving 100 variables, but that that could be reduced to manageable proportions through appropriate model partitioning. But with your man-in-the-loop simulation, you will be faced with an order of magnitude growth in simulation complexity and run-time. Do you plan to make use of statistical sampling techniques such as those used in psychological experiments to again reduce this problem to manageable proportions.

Author's response:

We plan to rely heavily on fractional factorial experiment designs. However, these have been applied in the past mainly to psychological experimentation and there is only limited experience with the type of investigations required in the IFFN evaluation. Therefore, a series of pilot experiments will be performed to confirm the applicability of fractional techniques. If these or other statistical techniques are found to be inappropriate, the fallback position will be to use a set of "standard" scenarios representing self-consistent sets of conditions. These scenarios might correspond to a "worst case," a "best case," and an "intermediate case" and would be agreed upon by the air defense community.

Comment by Dr. S. H. Starr, Institute for Defense Analyses, 400 Army Drive, Arlington, VA 22202, U.S.A.:

Let me comment on the overall schedule of this program. We're now in the process of doing a test design and are also planning the creation of the testbed. We anticipate the simulation to be in operation by 1982 and concluded by 1984. We are eager to cooperate with other interested groups such as SHAPE Technical Center, IABG, and NPC.

Comment by Mr. A. Bömisch, IABG, mbH, Einsteinstrasse 20, 8012 Ottobrunn, Federal Republic of Germany:

Regarding the modeling of communication functions, do you plan to implement event-oriented queuing of messages as affected by communication protocols? networking (routing)?

Author's response:

The operational communications network in the testbed will reproduce the connectivities and vulnerabilities of the actual NATO communications network. Provisions will also be included to establish the proper background loadings on the links so that the communications delays that would be experienced under wartime conditions will be emulated. Fast-time models and NATO field exercise data will be used to establish the values of the statistical measures of these delays for subsequent use in the testbed.

Paper No. 26 (Mr. Wunderlich)

Comment by Mr. H. R. Wilhelm, STC, P.O. Box 174, 2501 CD, The Hague, Netherlands:

I would like to express my appreciation for this interesting presentation on your model which will certainly find a wide application in the future. However, I am intrigued by your conception of escort fighters letting interceptors disengage if they want to, and in this way let the interceptor optimise their effectiveness (i.e., escort fighters cooperating with interceptors). The mission of escort fighters is to engage interceptors and in doing so distract them from their high priority targets--which are the escorted aircraft. By letting interceptors disengage, escort aircraft fail to perform their mission. In this context I have several questions. First, have you done any studies on the feasibility of disengagement taking into account improved firing ranges of modern air-to-air missiles?

Author's response:

This is a tactical question. In the presentation the assumption was made that blue fighters may leave the arena under the condition that they do not threaten the red fighter-bombers (FB's) any more. In this case it does not make sense for the escorts to engage the departing blue fighters since this increases the risk to the escorts tremendously (hostile environment, ground-based actions, etc.). So again, in my opinion, if escorts accept the combat termination offered by departing blue fighters, they do not fail in solving their mission but minimise their own risk.

Regarding the improved firing ranges of modern air-to-air missiles, there were no specific studies dealing with this subject. The disengagement logic is always active and in this case (improved firing ranges), is influenced by increasing passive threat values.

Comment:

Does your model have any disengagement logics? And, if not, do you intend to develop these logics?

Author's response:

There is a disengagement logic which tells the aircraft to try to leave the combat if possible (i.e., low passive threat values) in case of shortages in armament or fuel.

Comment:

How realistic is your assumption of cooperative behavior of two opposing forces?

Author's response:

Escort and FB are cooperative only at the beginning and in the first phase of combat as shown on the flight path plot. Once the escorts try to engage the blue fighters, they "forget" their FB's. Then, if an escort no longer has an opponent and cannot find one, he returns to base. This seems to be realistic, since on one hand after an air combat the escort does not have the chance to close up to his FB again; and on the other hand, he has not enough fuel left to fulfill his escort mission.

Comment:

How could the idea of optimizing the time of disengagement--if it were feasible--be implemented in reality?

Author's response:

This could be done by experience; i.e., based on the knowledge of performance data and numbers of aircraft, the leader may estimate a maximum combat time or an allowable loss-rate.

Comment by Ir N. Van Driel, N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands:

Which kinds of sensors are considered and to what level of sophistication?

Author's response:

The following sensors are included: pulse and pulse Doppler-radar (STT/TWS; i.e., multitarget capability), RHAW, FLIR, HMS, pilot's eyes (one-half person per A/C). Each sensor-model simulates the detection process in a moderately sophisticated manner by using the relevant equations. Example: FLIR takes into account wavelength, aerodynamic heating, plume, power setting, rain, etc.

Comment:

Could you give some information how the detection process is modeled?

Author's response:

The sensor models are handled by a "switch-pilot," which consists of certain algorithms which manage the "on/off" of all sensors. Example:

- Red has an SOJ; the red aircraft have activated all passive sensors; radar is quiet (in order not to act as a "beacon"!).

- Blue is searching with all sensors (active and passive). If no detection occurs after a certain time, then radar "off" for a specific time. Then once again, "Radar on Search," etc. Another example: - If more than "x" targets are within visual range, then radar "off," and rely on FLIR/RHAW/HMS.

There are more algorithms used which are similar to these examples.

Comment by Mr. J. H. Powell, Advanced Projects Dept. British Aerospace, Warton Aerodrome, Preston, Lancs, United Kingdom:

What account does your model take of classification times, bearing in mind that engagement may be delayed in the early stages of a conflict because of the possible limitations of not opening fire on a target which has not been positively identified?

Author's response:

Up to now there are no specific subroutines dealing with this subject. IFF is taken into account by various time delays (sensor-dependent).

Paper No. 27 (Cancelled)

Paper No. 28 (Dr. Ruddy)

No comments.

Paper No. 29 (Mr. Buisson)

No comments.

SESSION VI DISCUSSION

Paper No. 30 (Mr. Bannister)

Comment by Mr. M.D. Rigby, Aerodynamics Dept. British Aerospace, Aircraft Group, Warton Aerodome, Warton, Preston, PR 4 1AX, United Kingdom:

With reference to your remarks on the limitations encountered in implemintng digital solution techniques to your aircraft/control system/avionics system models in terms of iteration time, available storage, etc., can you make any comments on any areas in which solution by hybrid computing methods might be more advantageous, if you believe any exist?

Author's response:

While we recognise the advantages available from analog computing, particularly in terms of computing time, we have found the flexibility available from digital computing to be attractive. We have approached the requirement for additional processing power by using dedicated microcomputers to host the individual avionic system simulations and connect them by a multiplex digital data transmission system, much as would be done on an individual aircraft.

Comment:

When faced with a simulation task, do you find that your approach tends to be tailored by the type of computing facilities already available to you, or are you able to formulate your approach to the problem and specify the type of computing facility required accordingly?

Author's response:

Of course, the approach adopted always has to consider the resources available. However, the use of a modular approach using microcomputers provides us with a very flexible expansion capability.

Comment:

Are you always sure that the output from a much-simplified simulation model is a valid solution to your original more complex model?

Author's response:

As indicated in the paper, the level of complexity of the model has to be determined by the simulation objectives, and the simplest possible model should be adopted. However, I agree that it is necessary to be careful not to over-simplify, and it is important to examine any conclusions that may be drawn from simulation with respect to the simplifying assumptions included in the model.

Comment by Mr. R. Voles, Panel Member, EMI Electronics Ltd. 135 Blyth Road, Hayes, Middlesex UB3 1BP, United Kingdom:

In view of the continuing spectacular reduction in the cost of computing and in the light of the considerable success that has been achieved in computer chess-playing packages, is it not time to start thinking about taking a more positive attitude to the decision rules used in air-air combat and to evolve packages which will generate, ab initio, the optimal tactics to be adopted at each stage in multi-aircraft engagements?

Author's response:

As is implied by the question, the computing time required to explore this suggestion is extremely demanding. We understand that an approach has been made in the United States to applying optimised tactics at an elementary level using the Theory of Games, which confirms this conclusion.

Comment by Mr. F. S. Stringer, Panel Member, Royal Aircraft Establishment (R117 Bldg), Farnborough, Hants, United Kingdom:

Have you plans for the consideration of the assessment of benefits which may be expected from the use of pairs of aircraft operating in a mutually protective fashion, even in terms of one-on-one combat?

Author's response:

The development of the tactics routines which are very important in aircraft combat modeling has mainly been based on current Air Force practice. This has been achieved by regular discussion with active Air Force personnel. We accept that the whole question of cooperative operations in close combat is a controversial one. Our own view is that coordinated tactics will in practice rapidly degenerate into a

series of one-on-one combats occurring concurrently. This has been our approach to date although we have not precluded the possibility of modeling coordinated tactics in the future.

Paper No. 31 (Mr. Ostgaard, Presenter)

No comments.

Paper No. 32 (Mr. Morrow)

Comment by Mr. H. W. Pongratz, IABG Abt WTS, Einsteinstrasse 8012 Ottobrunn B. München, Federal Republic of Germany:

In our air-to-combat simulator there are several microcomputers, but we can at the moment parallel no more than about three machines. How many microprocessors do you think you can put in parallel before the data-bus becomes congested?

Author's response:

The number is dependent upon the two bus data rates; the input bus data rate should be kept small or multiplexed to groups of microcomputers. We see the output extending to handle 256 microcomputers or a data descriptor rate of 106 descriptors/sec. The basic concept is to use microcomputers as "LEGGO'S" (or "TINKER TOYS") to construct the most representative configuration.

Comment by Mr. B. Davy, MOD (UK) St. Andrews Road, Malvern Worcs, United Kingdom:

My first comment concerns the suggestion that micros are equated with cheap processing. The hardware may be very cheap, but the cost of programming is not. The cost of filling the 4K memory with debugged and documented code will be around $20K if using a high level language, and $100K or more if assembly language is used as suggested in the paper.

Author's response:

Cost is directly related to the number of lines of tested code. My premise is that the number of lines of code will be reduced significantly and the cost of testing is small for the total simulation as linear superposition holds for tested code used in adjacent computer units. A further significant cost advantage is through the use of a high level language to construct a scientific model of the simulated microcomputer function and hence to a tabular or logic structure suitable for loading in the target microcomputer as part of its operating software.

Comment:

My second comment is a query as to the extent to which the real world can be adequately represented by parallel autonomous processes. If, for example, an ESM carried by an aircraft detects a radar, then the aircraft may well change course, resulting in a change of aircraft position, ESM output, and radar output. When closed loops like this are taken into account, it seems to be that the fraction of the total workload which can be put out to parallel processing is very small.

Author's response:

The problem of representing realistic interaction between a moving platform and an array of emitters is a suitable problem for this parallel microprocessor approach.

Comment by P. M. Sepp, Industrieanlagen-Betriebsgesellschaft mbH, Studienabteilung WTS, 8012 Ottobrunn b. München, Einsteinstrasse, Federal Republic of Germany:

Our experience with an air combat flight simulator indicates that we can have not more than three or so microprocessors working together; otherwise they are essentially talking to each other instead of to our simulator. This is a problem we are working on now.

Author's response:

Certain problems do not "map" readily into this structure; but there is a large class of problems that do. I think the ESM problem "maps" very well, and so do many air defense modeling problems.

Paper No. 33 (Mr. Ostgaard)

Comment by Ir N. Van Driel, N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands:

In one of your slides the AEP Library was mentioned as one of the models for aircraft simulation. Can you give information on which parameters/models you are using from the AEP Library?

Author's response:

The AEP Library, though available, is currently not being used for the simulation involving the Dais System. Likewise, the AEP Library has grown so that it is now hosted on the CDC 6600 System.

Paper No. 34 (Mr. Pongratz)

Comment by Mr. C. M. McLean, British Aerospace Dynamics Gp. Hatfield/Lostock Div. Manor Road, Hatfield, Hertfordshire, United Kingdom:

How significant is the acceleration contribution to the accuracy of the prediction?

Author's response:

With a very manouverable target this contribution decides whether you hit a "jinking" target or not.

Comment:

Is the length of the computing time available in a gun firing opportunity sufficient to permit you to make sensible estimates of target acceleration in the noise environment which is likely to occur?

Author's response:

The gradient initialization phase is less than 1 second. This should be short enough.

Comment by Mr. J. H. Powell, Advanced Projects Dept. British Aerospace, Warton Aerodome, Preston, Lancs, United Kingdom:

What validation has been carried out on the model?

Author's response:

The model has been extensively tested with a rather detailed radar model off-line and on-line even under extreme conditions. This radar model was validated in another study before we used it for our system.

A test against reality using a low target would not be practical for this has not the maneuverability that would be required for a valid test.

Paper No. 35 (Mr. Bouthors)

No comments.

Paper No. 36 (Mr. Schmidt)

Comment by Dr. H. A. F. Roefs, National Aerospace Laboratory, NLR, Voorsterweg 31, Emmerloord, Netherlands:

I assume that the actual performance requirements for the cruise missile are classified which makes it difficult for me to check your result as far as the conclusion is concerned. But I take it that at least you conclude that you do not need NAV STAR GPS's performance?

Author's response:

That is correct. The paper does contain some details for the cruise missile navigation system that are unclassified. The only classified information has to do with land falls, map widths, and the like.

Comment by Ir H. A. T. Timmers, Panel Chairman, Head Electronics Dept. N.L.R. Anthony Fokkerweg, 2, 1059, CM Amsterdam, Netherlands:

An inertial system is sensitive to the direction of flight. There is a big difference in error build-up, especially during long flight time. For flights from east to west and west to east the difference is very great. Is this effect fully encompassed in your error calculations?

Author's response:

Yes, it is. Results for heading sensitivities were not included in the paper; however reference No. 7 contains a discussion of those effects. There is a big difference, especially at the longer flight times.

Comment by unknown source:

What is the gyro model used in the cruise missile alignment filter?

Author's response:

Actually it varied anywhere from 12 to 15 states. Typically it includes nine states for the inertial system, two for the doppler, and three for gyro bias.

Paper N° 37 (Mr.Erkelens)

Comment by Dr.L. Beck, Standard Electrik Lorenz AG, Dept. CNS/TWB, Hellmuth-Hirth Strasse 42, 7000 Stuttgart, 40, Federal Republic of Germany:

Basic for statistics: Only 3 pilots? I assume not enough for correct interpretation of the physical efforts of pilots!

Author's response:

I agree that from a statistical point of view a total of 3 pilots is small. However, in flight testing and simulation one is always very restricted in the number of subjects, because of available time and money. Apart from this there was a substantial difference in background and experience between the 3 pilots. Two of them were airline pilots, one with 600 hours experience on the B747 and one with 150 hours experience on the DC-10. The third pilot was an engineering pilot involved in airworthiness flight testing and with a total of 330 hours of wide body aircraft experience.

Comment by Mr. B.L. Dove, Panel Member, Head, Avionics Systems Research Branch, Flight Electronics Division, NASA Langley Research Center, Mail Stop 477, Hampton, VA 23665, USA:

Are the negative results you obtained in simulation attributable to the display you employed?

Are you familiar with the Terminal Configured Vehicle Program results of flight testing using airline pilots, and are your simulation results in agreement with TCV results? If not, why not?

Author's response:

As pointed out in the written paper the pilots did not use the pictorial display frequently. The following reasons were given:- the approach profiles were rather simple, - the display had been situated outside the scanning range of the pilots.

The results of this simulation largely agree with the automatic flown curved approaches of the B737 TCV of NASA. It has to be taken into account that there were significant differences between the simulator and the TCV instrumentation. In the TCV use was made of advanced electronic displays (EADI and EHSI) and moreover the NLR investigation included rather worse weather conditions (strong shears and low cloud base).

Comment by Mr. F.S. Stringer, Panel Member, Royal Aircraft Establishment (R177 Bldg) Farnborough, Hants, United Kingdom:

Please comment upon the use of the horizontal display used in your simulation. Would this have been of more benefit if it was used to investigate problems of curved approaches during partial system failure or for the investigation of reduced ATC instructions.

Author's response:

The pictorial display would have been more beneficial in case of a two pilots operation. The pilot-not-flying would be able to monitor the approach on the display up to the final segment. Also during the approach path interception phase this instrument could be of any help. Although no system failures have been considered in the investigation, I think the information on the present display is too course for

use as primary guidance. Use for ATC purposes would have required a different display lay-out.

Paper No 38 (Professor Danesi)

Not presented.

Paper No. 39 (Commander Lane)

Comment by Dr. J. Barratt, Head of Helicopter Displays Section, Flight Systems Dept. RAE, Farnborough, Hants, United Kingdom:

Could you say a bit more about the human operator model you mentioned?

Author's response:

This model has been under development for some time. The original idea was conceived over 10 years ago by Commander Robert Wherry, USN. It is based on a detailed task analysis of pilot and crew operations and actions. It is programmed in a specially developed language which uses a combination of English and FORTRAN: FORTRAN for expressing mathematical equations used to describe the operator's mental processes or the functioning of the hardware, and English to describe the procedures or actual steps that the operators carry out in flying an aircraft or performing any type of mission. The compiler converts these statements into a form that can be utilized by the simulator, which processes these statements, accessing certain micro-models for information absorption, perception, anatomical movement, short-term memory, etc. as needed. These micro-models are based on human performance experiments reported in the literature. The simulator then generates a time-line for the operator's performance. An output processor then generates statistical data based on the statistical characteristics of an average trained operator. Information on the model is readily available in the literature.

Comment by Mr. J. H. Powell, Advanced Projects Dept. British Aerospace, Warton Aerodome, Preston, Lancs, United Kingdom:

Utility and cost functions are difficult to assign to any operational task. How sensitive are your qualitative results to your assignments of the utility functions?

Author's response:

The results appeared to be far more sensitive to the tactics used in our simulation than to the assigned utilities. It's very difficult to obtain utilities; assignments of utilities need to be explicitly stated by a higher authority, and we are advocating this.

Comment by Mr. J. G. Wohl, Program Chairman, The MITRE Corporation, P. O. Box 208, Bedford, MA 01730, U.S.A.:

You've aggregated a number of micro-models of human cognitive and motor performance into a large-scale model purporting to reflect total human performance in a task. Has it been validated against a number of trained operators performing real tasks?

Author's response:

Yes, in limited circumstances it has been validated against a number of tasks.

Paper No. 40 (Dr. Linton)

No comments.

APPENDIX B

LIST OF ATTENDEES

ALBAUT	Thomson CSF, 178 Bld Gabriel Péri, 92240 Malakoff, France
ALBERTS, D.S. Dr	MITRE Corp., Wash. C^3 Div., 1820 Dolley Madison Bld, McLean, VA, USA
ALCOUFFE, G. Mr	Crouzet, 25 rue J.Védrines, 26016 Valence, France
ALVAREZ, E.S. Mr	The MITRE Corporation, P.O.Box 208, Bedford, Ma.01730, USA
ATTULY, R. Mr	Aérospatiale, Subdivision Systèmes, B.P.96, 78130, Issy-les-Moulineaux, France
AUDREN, Mr	SFIM, 13 Avenue Ramolfo Garnier, 91301, Massy, France
BALL, W.F. Mr Panel Member	Naval Weapons Center (Code 4041), Department of the Navy, China Lake, CA 93555, USA
BARRE, P. Mr. Panel Member	Service Technique des Télécommunications de l'Air, 129, rue de la Convention, 75996 Paris Armees, France
BARRETT, J. Dr	Head of Helicopter Displays Section, Flight Systems Dept., RAE, Farnborough, Hants, UK
BANNISTER, J.D. Mr	British Aerospace Aircraft Group, Kingston-Brough Division, Brough, North Humberside, HU15 1EA, UK
BECK, L. Dr	Standard Elektrik Lorenz AG, Dept.CNS/TWB, Hellmuth-Hirth Strasse 42, 7000 Stuttgart, 40, FRG
BENNIS, H.G.M. Ir.	Physics Lab. TNO, P.O.Box 96864, 2509 JG, The Hague, Netherlands
BERCOVICI, Mr	SNIAS, HDE EQ, B.P.13, 13722 Marignane, France
BERTIN, C. Mr	Aérospatiale, Subdivision Systèmes, B.P.96, 78130 Issy-les-Moulineaux, France
BLANC, Mr	STAE, 4, Avenue de la Porte d'Issy, 75015 Paris, France
BOEMISCH, A. Mr	IABG, mbH, Einsteinstrasse 20, 8012 Ottobrunn, FRG
BORAWITZ, W.C. Ir.	Physics Lab. TNO, P.O.Box 96864, 2509 JG, The Hague, Netherlands
BOSNELL, J.R. Dr	R.S.R.E., St Andrews Road, Malvern, Worcs, UK
BOUTHORS, E. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214 St Cloud, France
BRAULT, Y. Mr Panel Member and Host Coordinator	Thomson CSF, 178 Avenue Gabriel Péri, 92240 Malakoff, France
BROOK, P. Mr	G.Building, MOD (PE), R.S.R.E., St Andrews Road, Malvern, Worcs, UK
BUISSON, D. Mr	Aérospatiale, Subdivision Systèmes, B.P.96, 78130 Issy-les-Moulineaux, France
CAMBERLEIN, L.	SAGEM, 6, Avenue d'Iéna, 75016 Paris, France
CATANI, Mr	SNIAS, HDE EQ, B.P.13, 13722 Marignane, France
CATEL, P. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214 St Cloud, France
CERETTI, F. Ing.	Contraves Italiana, Via Tiburtina, Km 13.15, 00131, Roma, Italy
CHADEAU, Mr	STAE/EQ, 4, Avenue de la Porte d'Issy, 75015 Paris, France
CHATELOT, J.F. Mr	SAGEM, Chaussée Jules César, Osny, France
CHERMETTE, D. Mr	SAGEM, 6, Avenue d'Iéna, 75016 Paris, France
COOPER, C.W. Mr Panel Member	R.S.R.E., St Andrews Road, Malvern, WR14 3PS, UK
CORAZZA, G. Prof. Panel Member	Universita Bologna, Villa Griffone 40044, Pontecchio Marconi, Bologna, Italy
COUDRAIS, J.M. Mr	Electronique Marcel Dassault, 44 Quai Carnot, 92214 St Cloud, France
COWDREY, P.R. Mr	British Aerospace Aircraft Group, Woodford, Stockport, Cheshire, UK
CRITCHLEY, I.R. Col.	Marconi Space & Defence Systems Ltd., Hillend, Nr Dunfermline, Fife, Scotland, UK
DARBYSHIRE, B. Mr	279 Highfield Road North, Chorley, Lancs, UK

DAVY, B. Mr	MOD (UK), St Andrews Road, Malvern, Worcs, UK
DE CREMIERS, M. Mr	SAGEM, 6, Avenue d'Iéna, 75016 Paris, France
DEDIEU, F. Mr	SAGEM, Chaussée Jules César, ZI d'Osny, 95000 Cergy-Pontoise, France
DEFEUILLEY, Mr	TRT, 5, Avenue Réaumur, 92350 Le Plessis Robinson, France
DIAMOND, F.I. Dr Panel Member	Technical Director, Communications & Control Div., Rome Air Development Center, (AFSC) Griffiss Air Force Base, N.Y. 13440, USA
DIAZ, S.A. Mrs	STC, P.O. Box 174, 2501 CD, The Hague, Netherlands
DOVE, B.L. Mr Panel Member	Head, Avionics Systems Research Branch, Flight Electronics Division, NASA Langley Research Center, Mail Stop 477, Hampton, VA 23665, USA
DOSTERT, K. Mr	Universitat Kaiserslautern, FB Elektrotechnik, Postfach 3049, 6750 Kaiserslautern, FRG
DREYFUS, M.G. Mr	LMT, Thomson CSF, 3, Avenue A. Einstein, 78192, Trappes CEDEX, France
DUCEAU, L. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214 St Cloud, France
DUDEK, L. Mr	ESG Elektronik System GmbH, Postfach 80 05 69, 8000 München, 80, FRG
DUNCAN, I. Mr	Ferranti Ltd., Ferry Road, Edinburgh, Scotland EH5 2XS, UK
EASDALE, B.R. Mr	Marconi Space & Defence Systems Ltd., Hillend, Nr Dunfermline, Fife, Scotland, UK
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FALCIASECCA, G. Prof.	Universita Bologna, Villa Griffone 40044, Pontecchio Marconi, Bologna, Italy
FIELDS, C.I. Dr	Cybernetics Technology Office, Defence Advanced Research Projects Agency, 1400 Wilson Blvd, Arlington, VA 22209, USA
FORNARI, M. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
FOUCHE, M.H. Mrs	Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
FRANKE, H.M. Dipl. Ing.	c/o Industrieanlagen Betriebsgesellschaft mbH, Einsteinstrasse, D-8012 Ottobrunn, FRG
FRANGIONE, F.A. Mr	The MITRE Corporation, MITRE C³ Div., 1820 Dolley Madison Bld, McLean, VA 22102, USA
FREEDMAN, J.E. Mr	Institute of Defense Analysis, 400 Army Drive, Arlington, Va, USA
FROMM, J.	DFVLR-VO-PV, Linder Hohe, 5000 Köln, 90, Germany
GOLDSTEIN, S. Mr	Electronique M.Dassault, 92214 St Cloud, France
GORI, M. Ing.	Face Standard Laboratorio Centrale Industrie, 00040 Pomezia, (Roma), Italy
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GRISON, Mr	Centre d'Essais en Vol, 13128, Istres-Air, France
GRUNEBERG, D.S. Mr	Marconi Space & Defense Systems, Hillend Industrial Estate, Hillend, Fife, UK
GUTMAN, L.L. Mr	Air Force Avionics Lab., AFAL/AAD, Wright Patterson AFB, Ohio, USA
HAMPTON, D.E. Mr	Supt. G.2. Div. R.S.R.E., St Andrews Road, Malvern, WR14 3PS, UK
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HEALY, R.D. Mr	Analytic Sciences Corp., 6 Jacob Way, Reading, Mass.01867, USA
HECKETSWEILLER, C. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
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HERZMANN, F. Mr	ESG Elektronik System GmbH, Postfach 80 05 69, 8000 München, FRG
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LAGARDE, X. Mr	SAGEM, 6, Avenue d'Iéna, 75016 Paris, France
LANE, N.E. Cdr.	Code 6021, Naval Air Develop. Center, Warminster, PA 18974, USA
LANGELIER, G.P. Mr	The MITRE Corporation, P.O.Box 208, Bedford, MA 01730, USA
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LINTON, P.M. Dr	Code 6021, Naval Air Development Center, Warminster, PA 18974, USA
LLOYD, K.H. Mr	R.S.R.E., St Andrews Road, Malvern, WR14 3PS, UK
LUEG, H. Prof. Dr Panel Member	Institut für Technische Elektronik der RWTH Aachen, Templergraben 55, D-5100 Aachen, FRG
LYNCH, U.H.D. Lt.Col.	Tactical Systems Division, DCS/Studies and Analysis, Headquarters USAF/SAGR, Washington, D.C. 20330, USA
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MCLEAN, C.M. Mr	British Aerospace Dynamics Gp. Hatfield/Lostock Div., Manor Road, Hatfield, Hertfordshire, UK
MIGINIAC, Mr	Avions Marcel Dassault, Division Système d'Armes, 78 Quai Carnot, 92214, St Cloud, France
MORROW, R.J. Mr	British Aerospace, Dynamics Group, P.O. Box No.77, Bld 16V, Filton House, Bristol, BS99 7AR, UK
MUENIER, M. Mr	EMD, 55 Quai Carnot, 92 St Cloud, France
MUELLER, D.	Siemens, Wv Fu Ort.ES11, Hofmannstr.51, 8000 Munchen, 72, Germany
MUSCINE[illegible], M. Dr	Contraves Italiana, Via Tiburtina, Km 13.15 00131, Roma, Italy
NEWMAN, S. Mr	Naval Air Development Center, Code 4012, Warminster, [illegible] 18974, USA
NOUVELLON, J. Mr	SAGEM, 6, Avenue d'Iéna, 75016 Paris, France
NOUYRIGAT, Mr	SECRE, 214 Faubourg St Martin, 75010 Paris, France
NOZ, W.A. Ir.	Physics Lab. TNO, P.O.Box 96864, 2509 JG, The Hague, Netherlands
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OGDEN, P.G. Mr	Marconi Avionics Ltd., Christopher Martin Rd., Basildon, Essex, UK
OLIVERO, S. Mr	S.I.A. Via Canova, 25, 10126, Torino, Italy
ORLANSKY, J. Dr	Institute for Defense Analyses, 4000 Army Drive, Arlington, VA 22202, USA
OSTGAARD, J.C. Mr	Air Force Avionics Laboratory/AAS, Wright Patterson AFB, 45433, USA
PAGNIEZ, Mr	Avions Marcel Dassault, Division Système d'Armes, 78 Quai Carnot, 92214, St Cloud, France
PALLAS, I. Dr	SCS, GmbH, Oehleckering 40 D-2000 Hamburg 62, FRG
PASQUET, Mr	SFENA, Aerodrome de Villacoublay, B.P. 59, 78140, Velizy-Villacoublay, France
PEEBLES, K.A. Mr Panel Member	Defence Research Establishment, Ottawa National Defence Headquarters, Ottawa, Ontario, KIA 0ZA, Canada
PEDOTTI, J. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
PERIN, J. Mr	Directeur des Services Logiciels, Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
PETERSEN, N.T.R. Mr	Danish Defence Research Establishment, Staunings Plads 2, DK 2100, Copenhagen Ø, Denmark

PLOUHINEC, R. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
PONGRATZ, H.W. Mr	IABG Abt WTS, Einsteinstrasse 8012 Ottobrunn B., München, FRG
PONS, J. Mr	Aerospatiale, 37 Bld Montmorency, 75016 Paris, France
POWELL, J.H. Mr	Advanced Projects Dept. British Aerospace, Warton Aerodrome, Preston, Lancs, UK
RAVAT, C. Mr	178, Bld Gabriel Péri, 92240 Malakoff, France
RHODES, S. Mr	RACAL. SSA Ltd., Basingstoke Road, Spencers Wood, Reading, Berks, UK
RICHARDS, R. Mr	British Aerospace, Dynamics Group, P.O.Box No.77, Bld 1bV, Filton House, Bristol, BS99 7AR, UK
RIGBY, M.D. Mr	Aerodynamics Dept. British Aerospace, Aircraft Group, Warton Aerodrome, Warton, Preston, PR4 1AX, UK
RIVIERE, R. Mr	Dornier, Dept. A.Y. 799 Friedrichshafen, FRG
ROEFS, H.A.F. Dr	National Aerospace Laboratory, NLR, Voorsterweg 31, Emmerloord, Netherlands
ROOME, G. Mr	Communications Technology, Boeing Aerospace, USA
ROWLEY, J.D. Mr	15 Alder Grove, Lytham, Lancs, UK
RUDDY, J. Dr	The MITRE Corporation, P.O.Box 208, Bedford, Ma 01730, USA
SAIB, S.H. Dr	General Research Corporation, P.O.Box 6770, Santa Barbara, CA 93111, USA
SARGENT, R.G. Dr	Department of Industrial Engineering and Operations Research, Syracuse University, 441 Link Hall, Syracuse, N.Y. 13210, USA
SCHAAFF, H. Mr	Federal College for Military Administration & Technology, Secken Heimer Landstr. D-6800 Manheim, FRG
SCHMIDT, G.T. Dr	Guidance and Navigation Advanced Program Div., Charles Stark Draper Lab., Cambridge, MA 02139, USA
SCHUBERT, H. Dipl. Ing.	DFVLR, Institut fur Dynamik der Flugsystem, Oberpfaffenhofen, 8031 Wessling/obb, FRG
SEPP, P.M. Dr	Industrieanlagen-Betriebsgesellschaft mbH, Studienabteilung WTS, 8012 Ottobrunn b. München, Einsteinstrasse, FRG
SETTERLUND, R.H. Mr	Guidance and Navigation Advanced Programs Div., Charles Stark Draper Lab., Cambridge, MA 02139, USA
SHANAHAN, A.R. Mr	The MITRE Corporation, P.O.Box 208, Bedford, MA 01730, USA
SIFFERMANN, V. Miss	SAGEM, 6, Avenue d'Iéna, 75016 Paris, France
STARR, S.H. Dr	Institute for Defense Analyses, 400 Army Drive, Arlington, VA 22202, USA
STITGER, L. Mr	CAWCS, Nieuwe Haven, Den Helder, Netherlands
STOLL, M. Mr	Electronique Marcel Dassault, 55 Quai Carnot, 92214, St Cloud, France
STRIEB, M.I. Mr	Analytics Incorporated, 2500 Maryland Road, Willow Grove, PA 19090, USA
STRINGER, F.S. Mr Panel Member	Royal Aircraft Establishment (R177 Bldg), Farnborough, Hants, UK
SUETA, T.J. Mr Panel Member	Deputy Director, Avionics Laboratory (DAVAA-D), US Army Electronics Command, Fortmonmouth, N.J. 07003, USA
SUTHERLAND, D. Mr	Marconi Avionics Ltd., Elstree Way, Borehamwood, Herts, UK
SWOROBOWICZ, C.J. Mr	The MITRE Corporation, Bedford, MA 01730, USA
TAILLET, J. Dr Panel Member	ONERA, 29, Avenue de la Division Leclerc, 92320 Chatillon-sous-Bagneux, France
TAYLOR, B. Mr	Marconi Avionics Ltd., Old Parkbury Lane, Coloney Street, St Albans, Herts, UK
TEMME, G. Mr	Civil Aviation Authority, Dept. of Airworthiness/Noise Affairs, Building 144, 1117 AA Schiphol Oost, Netherlands
TIMMERS, H.A.T. Ir. Panel Chairman	Head Electronics Dept., N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands
VAGNARELLI, F.Lt.Col.	Aeronautica Militare Italiana, Ufficio del Delegato Nazionale all AGARD, 3, Ple Adenauer, Roma, Italy
VANDECASTEELE, B. Ing. Pal.	S.T.A. 4, Avenue de la Porte d'Issy, 75996, Paris Armees, France
VAUGHN, R.S. Mr	Director, Sensors & Avionics Technology Directorate, Naval Air Development Center (30) Warminster, PA 18974, USA
VAN DRIEL, N. Ir.	N.L.R. Anthony Fokkerweg 2, 1059, CM Amsterdam, Netherlands

VOGEL, M. Mr Panel Deputy Chairman	DFVLR, NE-HF, D-8031 Oberpfaffenhofen, FRG
VOLES, R. Mr Panel Member	EMI Electronics Ltd., 135 Blyth Road, Hayes, Middlesex, UB3 1BP, UK
WELCH, J.A. Jr. Maj. General	Assistant Chief of Staff/Studies and Analysis, Headquarters US Air Force, Washington D.C. 20330, USA
WICHMANN, F. Mr	Industrieanlagen Betriebsgesellschaft mbH, D.8012 Ottobrunn, Einsteinstrasse, FRG
WILHELM, H.R. Mr	STC, P.O.Box 174, 2501 CD, The Hague, Netherlands
WOHL, J.G. Dr Program Chairman	The MITRE Corporation, P.O.Box 208, Bedford, MA 01730, USA
WUNDERLICH, G. Mr	Industrieanlagen Betriebsgesellschaft mbH, D.8012 Ottobrunn, Einsteinstrasse, FRG
WUNSCHMANN, H.J. Lt.Col.	NPC GLONS, Kaserne Ambidrix, Blaarstraat, 99, B.3700 Tongeren, Belgium

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REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-CP-268	ISBN 92-835-0255-8	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	MODELING AND SIMULATION OF AVIONICS SYSTEMS AND COMMAND, CONTROL AND COMMUNICATIONS SYSTEMS
7. Presented at	a Meeting of the Avionics Panel held in Paris, France, 15–19 October 1979.

8. Author(s)/Editor(s)	9. Date
Various	January 1980

10. Author's/Editor's Address	11. Pages
Various	572

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Avionics	Airborne operations
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Telecommunication	Simulators
Air defence	Mathematical models

14. Abstract

These Proceedings consist of the papers and discussions presented at the Avionics Panel Meeting on Modeling and Simulation held in Paris, France, October 1979. Papers were divided as follows: 6 – Tutorial, 8 – C^3_u System Simulation, 5 – Airborne Surveillance System Simulation, 5 – Manned Flight Simulators, 4 – Identification, Communication Navigation, and Countermeasure Simulation, and 11 on Avionics System Simulation.

AGARD Conference Proceedings No.268
Advisory Group for Aerospace Research and Development, NATO
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